RiskPoll: A model for quantifying air emission impacts and damage costs to human health and the environment

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Outline

- ExternE project of the EC
- RiskPoll assessment for classical pollutants
- RiskPoll multimedia assessment
- Uncertainty of damage costs
- References

ExternE Project of the European Commission

Further reading at http://www.europa.eu.int/

ExternE Project

- ExternE ⇒ Externalities of Energy
- The ExternE project has been funded by the European Commission, DG XII Science, Research and Development since 1991.
- The goal of this work has been to develop a transparent, consistent and comprehensive framework for identifying and quantifying the environmental impacts and damage costs of electricity generation, transport and waste incineration in Europe.
- Over 100 scientists from all countries of the European Union have participated since the start of the project.
- Major publications in 1995, 1998, 2000 and 2004.
- Ongoing projects NEEDS, METHODEX, MAXIMA, etc.

ExternE Methodology

- A “bottom-up” approach is used to quantify the physical impacts and damage costs based on a site-specific “Impact Pathways Analysis”

SOURCE
(specification of site and technology)
⇒ **emission**
(e.g., kg/yr of particulates)

↓

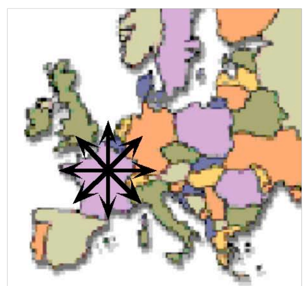
DISPERSION
(e.g. atmospheric dispersion model)
⇒ **increase in concentration at receptor sites**
(e.g., $\mu g/m^3$ of particulates in all affected regions)

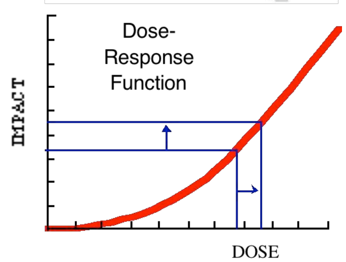
↓

DOSE-RESPONSE FUNCTION
(or concentration-response function)
⇒ **impact**
(e.g., cases of asthma due to ambient concentration of particulates)

↓

MONETARY VALUATION
⇒ **cost**
(e.g., cost of asthma)





<u>Physical impacts & economic costs</u>

(damages and externalities) are calculated by tracing the <u>fate</u> of a pollutant from point of emission, air dispersion and chemical transformation, receptor uptake, and estimation of the resulting impacts and costs.

<u>External cost</u>

Exploitation of any energy source generates damages that are borne by society as a whole and are not reflected in market transactions.

ExternE Project – Case studies

- Electricity fuel chains
  - Fossil fuels (coal, oil, lignite, gas and peat)
  - Renewables (wind, PV, biomass and hydro) and Nuclear power
- Transport
  - Cars, motorcycles, trucks, buses, rail, ship and airplanes
- Waste incineration
  - Municipal solid waste, cement kilns

Quantify impacts and damage costs to

- Public health (morbidity & mortality), crops, fisheries and building materials
- Amenity losses (noise, odor, visual impairment)
- Global warming and critical load exceedence (acidification, eutrophication)

ExternE Project – Applications

- Externalities have been used by the EC in developing various legislations in the energy sector (through the use of cost-benefit analysis), e.g.
  - Directive on air quality standards for
    - PM_{10}, SO_2, NO_2 and lead
    - Ozone
    - CO and benzene
    - PAHs
    - Cd, Cr, Hg and Ni
  - Large combustion plant directives (setting emission standards)
  - National emission ceilings for SO_2, NOx, VOCs and NH_3
  - Directive on emissions from waste incineration
  - Directive on sulfur content of marine fuels
  - Levels of permitted support for renewable energy technologies (based on externality differences between fossil fuels and renewables)
  - Developing sectoral targets for reducing emissions of CO_2
  - Further developments will be carried out in the Clean Air for Europe CAFÉ program

Further reading at http://www.europa.eu.int/comm/environment/pubs/studies.htm

RiskPoll assessment for classical pollutants

See references for further reading

The need for simplicity

- Usually, people tend to use site-specific results as if they where typical values ⇒ *precisely wrong rather than approximately right*.
- Most policy applications need typical or aggregated values instead of “worse” case scenario or “conservative” estimates.
- Detailed environmental impact analyses (EIA) are time intensive exercises that require in addition to physical resources:
  - extensive databases of knowledge, analytical tools, and know-how covering many fields of expertise (multi-disciplinary analysis); and
  - trained personnel to select the most appropriate input parameters, run the models and interprete the results.
- Oftentimes, EIA software is a “black box”, with assumptions and computation routines that are not at all transparent to the analyst. *Hence, there is a need to perform a “sanity” check of the results*.

Introduction

- RiskPoll is a set of "simplified" risk assessment tools for quantifying impacts to public health, agricultural crops and building materials following routine airborne emissions.
- Currently, the model can assess the local and regional impacts and damage costs associated with
  - respiratory health diseases from exposure to PM, SO_2, NOx, CO, secondary aerosols and user specified pollutants (inhalation pathway),
  - changes in crop yield from exposure to SO_2,
  - surface area of materials damaged from exposure to SO_2, and
  - toxic metal emissions (multimedia assessment).
- Future plans include radionuclide assessment and water pollution.

Introduction (2)

- The RiskPoll methodology has the advantage of being
  - transparent
  - simple to use, and
  - requires fewer input data – the simplest estimate requires only 4 numbers.
- Health risk assessment
  - Four models are available, each using a different methodology and input dataset (based on "availability") to quantify physical impacts and damage costs.
- RiskPoll provides results that are "reasonably" accurate and reliable as shown by comparison with detailed models. Usually, deviations for site-specific sources are less than ±50%.

Introduction (3)

- Intended uses of RiskPoll include:
  - process or technology evaluation,
  - comparative analysis of energy choices (e.g., fossil vs. renewables, …),
  - land use planning (e.g., siting of industrial sources, power plants, …),
  - ranking and cost-effectiveness of environmental mitigation and policy options,
  - viability of sustainable development strategies (e.g., by investigating the role of environmental regulations in shaping the future development of a country’s power sector – energy mix),
  - to assist the analyst who is faced with insufficient data, limited resources or lack of manpower to carry out a detailed assessment,
  - to serve as a “sanity” check to verify the “correctness” of detailed analysis results (e.g., screening of technical and/or human errors),
  - etc.

The Uniform World Model (UWM)

- Risk assessment routines in RiskPoll are based on the UWM estimation.
- UWM key assumptions
  - source-based coordinate system
  - steady emission rate Q
  - stack parameters are not considered (e.g., stack height h_S)
  - uniform population distribution r_{avg} (sum of receptors averaged over land and water; range of impact depends on source location: 500 km when source is located near a large city, otherwise 1000 km)
  - uniform dispersion & chemistry (processes characterized by the depletion velocity k)
  - linear, no threshold ERF, f_{ER}
  - mean unit values (costs), U_v .

The Uniform World Model (2)

- The damage cost D is calculated using the relationship

$$D = \frac{\tilde{n}_{avg}\ f_{ER}\ Q\,U_v}{k}\ R, \quad \text{with} \quad R = \int_{\text{Area of impact}} \frac{\tilde{n}(r,\theta)}{\tilde{n}_{avg}}\ \frac{M(r,\theta)}{Q}\ r\ dr\ d\theta$$

M(r,q) = pollutant ground-level removal flux from deposition and chemical transformation;
r (r,q) = population distribution.

- Elevated point sources
  - R ≤ 7 for site-specific industrial or power plant emissions
  - but, R is typically ≤ 2 (except when source is close to a large city, then R ~ 5)
  - for aggregated calculations involving sources located at different sites and with different characteristics, particularly stack height, R ~ 1
- Ground-level emission sources
  - R ~ 1 in rural areas
  - R up to 100 for releases near urban centers
  - R = 10 to 20 for aggregate ground-level emissions

The Uniform World Model (3)

- For a uniform receptor density, R = 1, and by conservation of matter:

$$UWM\ damage\ cost = \frac{\tilde{n}_{avg}\ f_{ER}\ Q\ U_v}{k}$$

- Equation can be used for both primary and secondary species provided the depletion velocity includes the chemical transformation rate (PM$_{10}$◊ k ranges from 0.6 to 0.9 cm/s in Europe; but can be as high as 3 cm/s in Brazil.)
- UWM is exact for uniformly distributed sources. Therefore, UWM provides “typical” damage cost results, which is what is needed for environmental policy taking decisions.

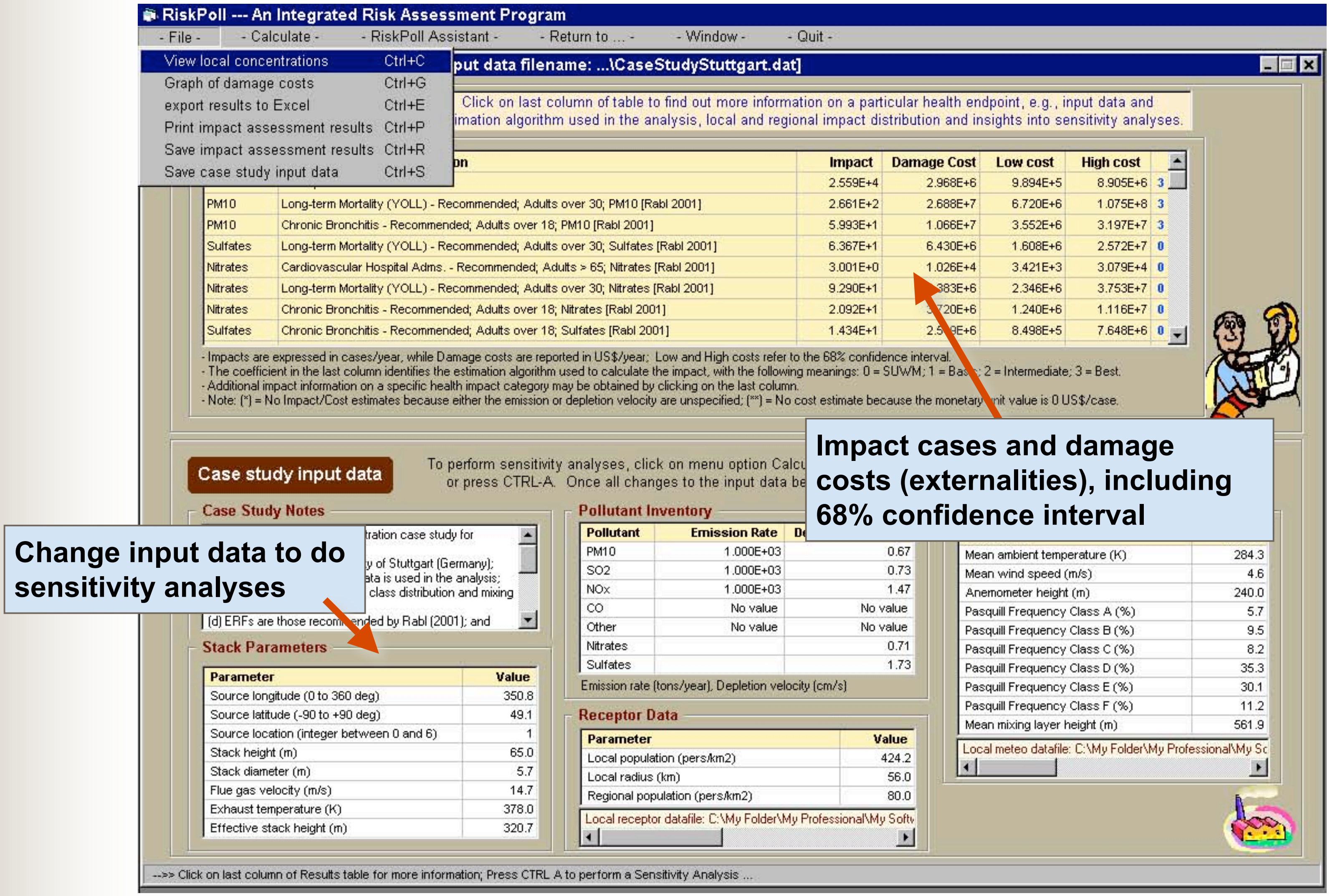
Health risk assessment input data requirements

Parameter	SUWM	RUWM Intermediate	RUWM Best	QUERI Basic	QUERI Intermediate	QUERI Best	URBAN
Local characteristics							Applies to urban sites only
○ Urban or rural location		ü	ü	ü	ü	ü	
○ Receptor density		ü	ü	‡	ü		
○ Receptor data (5 by 5 km^2)		†	†			ü	ü
Regional characteristics							
○ Receptor density	ü	ü	ü	ü	ü	ü	ü
Local weather data							
○ Mean wind speed			ü				ü
○ Mean ambient temperature			ü				ü
○ Pasquill class distribution			ü				ü
○ Detailed hourly data			§			ü	§
Stack data							
○ Height			ü		ü	ü	ü
○ Exit diameter			ü			ü	ü
○ Exhaust gas temperature			ü	‡	‡	ü	ü
○ Exhaust gas velocity			ü	‡	‡	ü	ü
○ Pollutant emissions	ü	ü	ü	ü	ü	ü	ü
○ Pollutant depletion velocity	ü	ü	ü	ü	ü	ü	ü
Other							
○ ER functions	ü	ü	ü	ü	ü	ü	ü

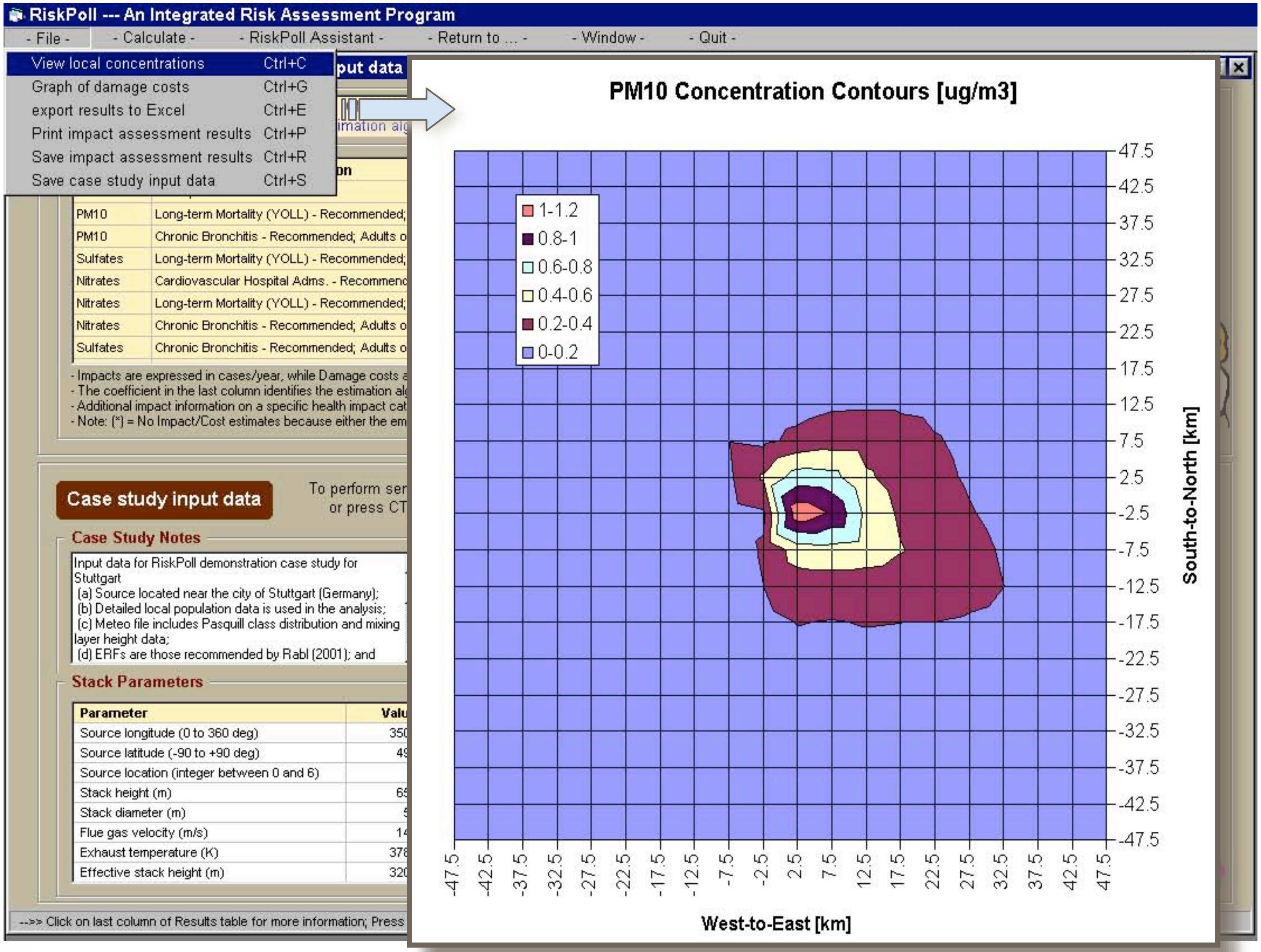
ü mandatory input datum
† can be substituted for the local receptor density
§ can be substituted for weather statistics
‡ if known an improved impact estimate will be calculated

All models share the same Basic estimate result

RiskPoll output options

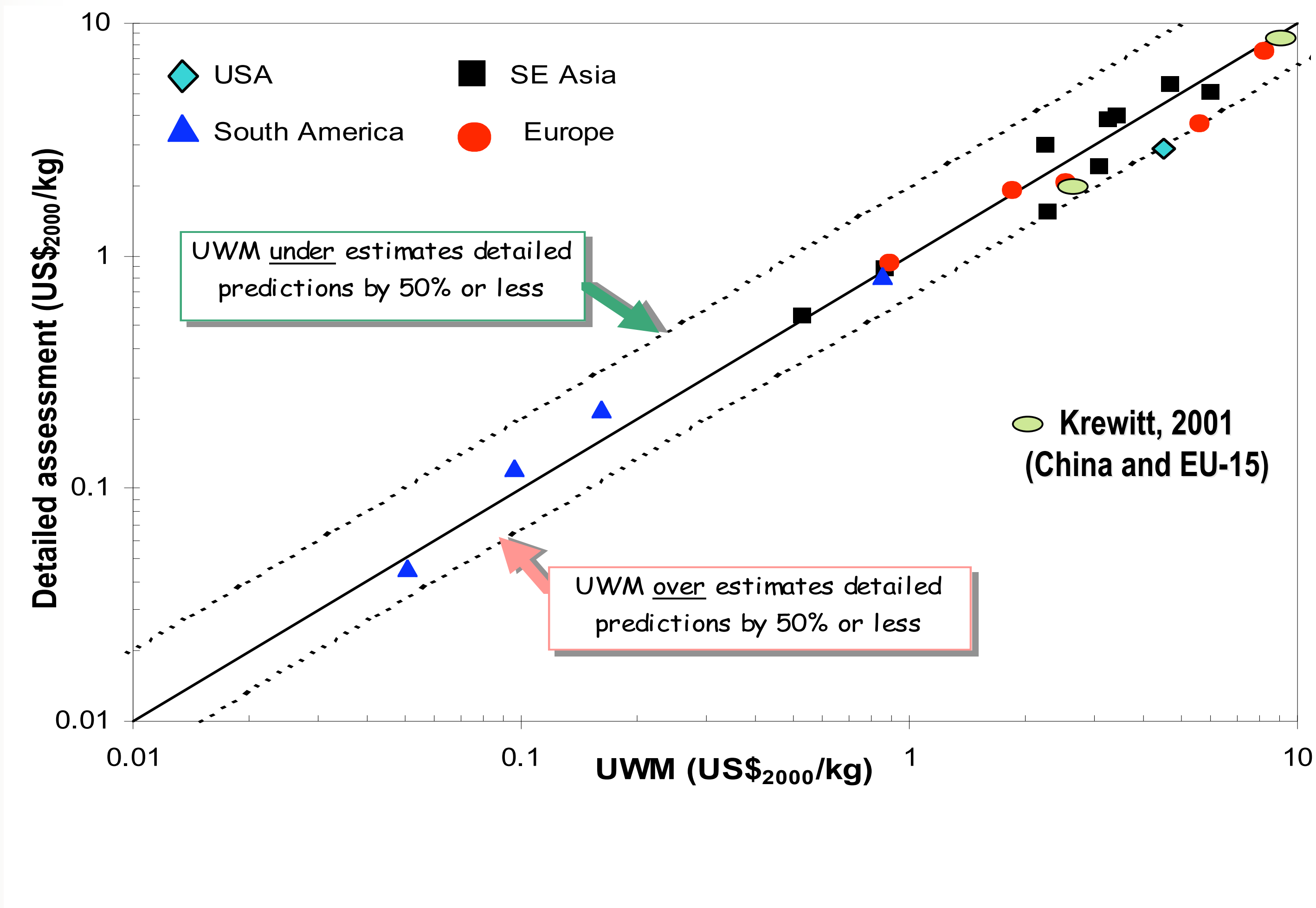


RiskPoll output options (2)



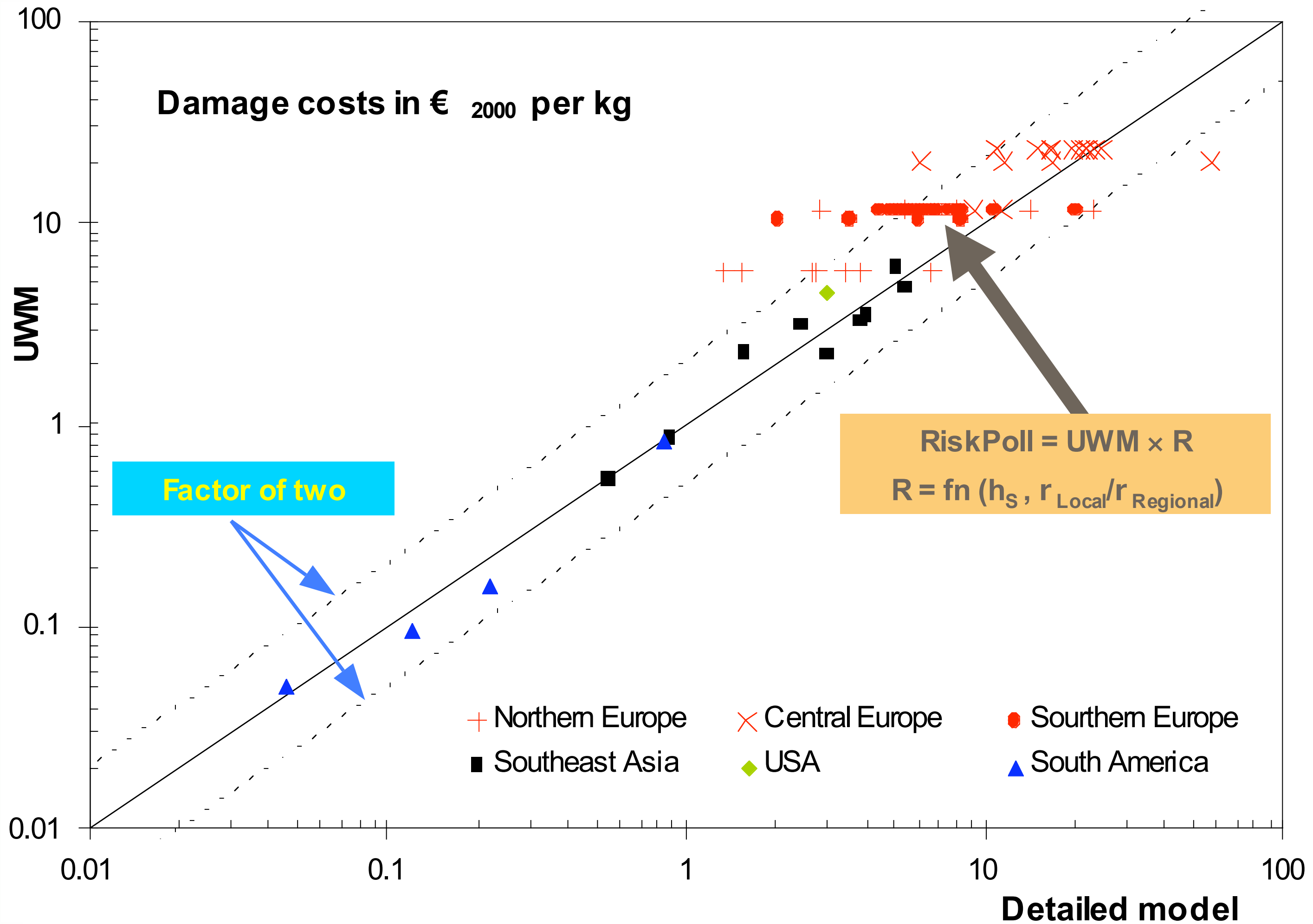
Validation studies

- Detailed model vs. UWM – PM_{10} (coarse local resolution, 50 x 50 km)



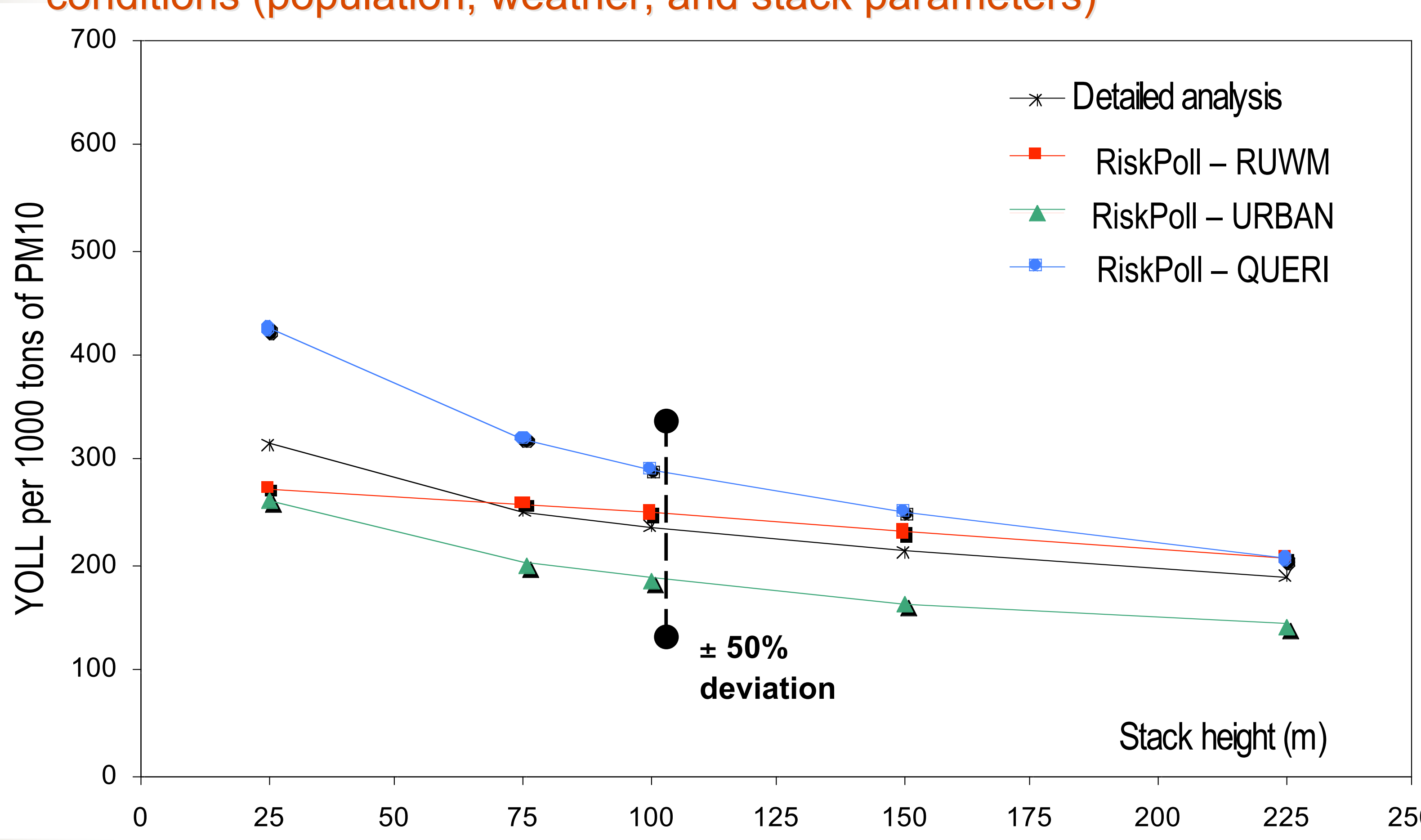
Validation studies (2)

- UWM vs. detailed model – PM_{10} (fine local resolution, 10 x 10 km)



Validation studies (3)

- Emission source located near Stuttgart, Germany: account for local conditions (population, weather, and stack parameters)



YOLL = Aggregate Years of Life Lost (loss of life expectancy) across Europe

RiskPoll case studies

- A (partial) list of studies that have used RiskPoll
  - ExternE, EU (part of impact assessment methodology)
  - NewExt Project, EU (country-specific unit damage costs)
  - ExternE-Poll Project, EU (multimedia assessment of toxic metals)
  - CETP, China (health impact assessment of air pollution for the Shandong region)
  - Health impact estimates of major thermal power plants in Pakistan (Pakistan Atomic Energy Agency)
  - An assessment of the practicality of renewable energy resources in Poland (Agencja Rynku Energii S.A.)
  - Health impacts of electricity in Brazil (Ministry of Science & Technology)
  - Comprehensive Assessment of Different Energy Sources for Electricity Generation in Indonesia (study requested by the Indonesian Government under a Technical Cooperation project sponsored by the IAEA).

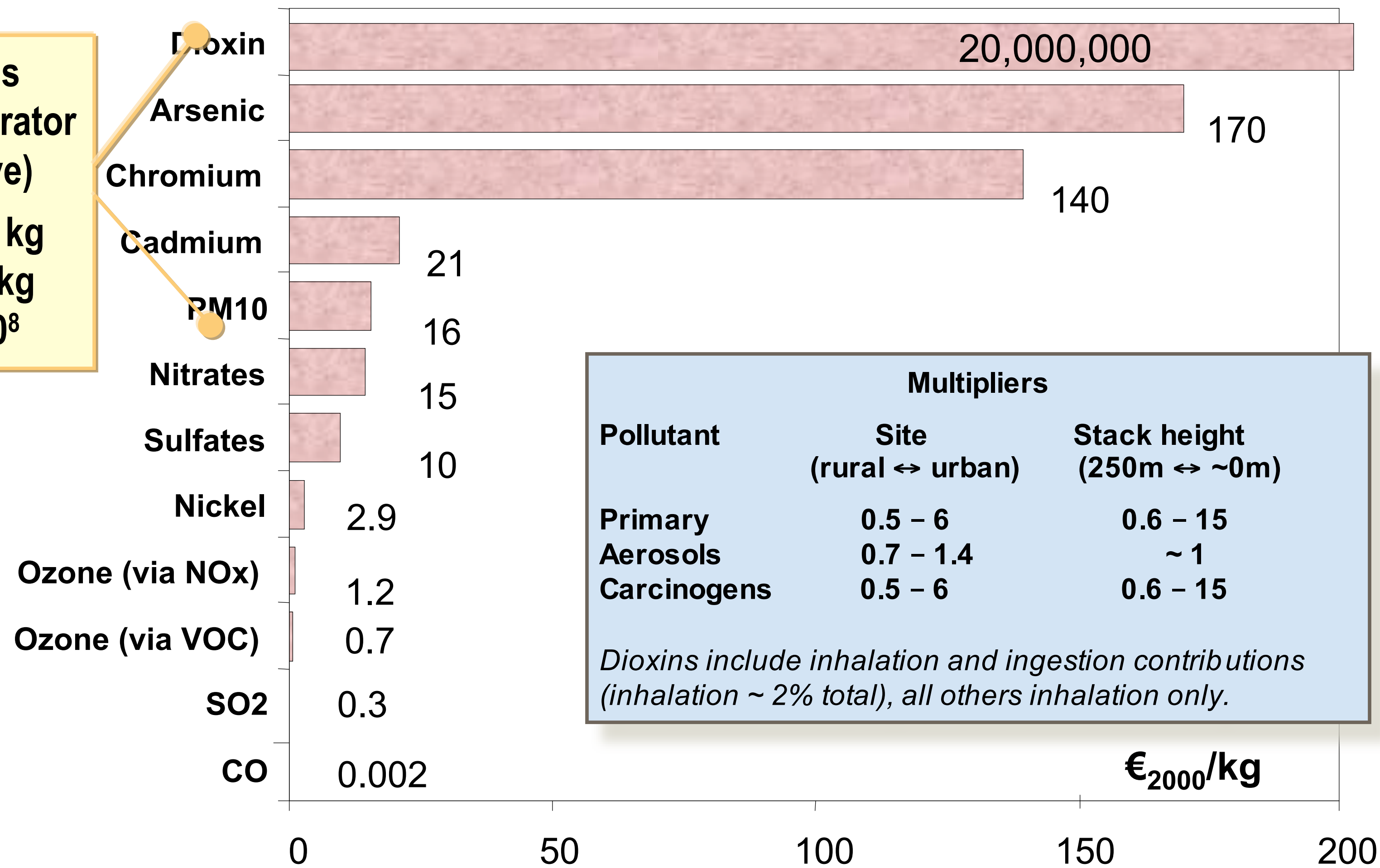
Examples

- Damage costs per kg of pollutant for Europe
- Life-cycle damage costs for automobile emissions in Europe and the US
- Damage costs internalization in the Indonesian power sector (Java Island case study)
- Social costs of electricity generation in Europe and South Africa
- Cost effectiveness of retrofit options in the power sector
- Individual lifetime risks

Typical damage cost per kg of pollutant for Europe

Annual emissions for typical incinerator (EC 2000 directive)

Dioxins: 0.00013 kg
PM_{10}: 13,000 kg
PM_{10} / dioxins: 10^8



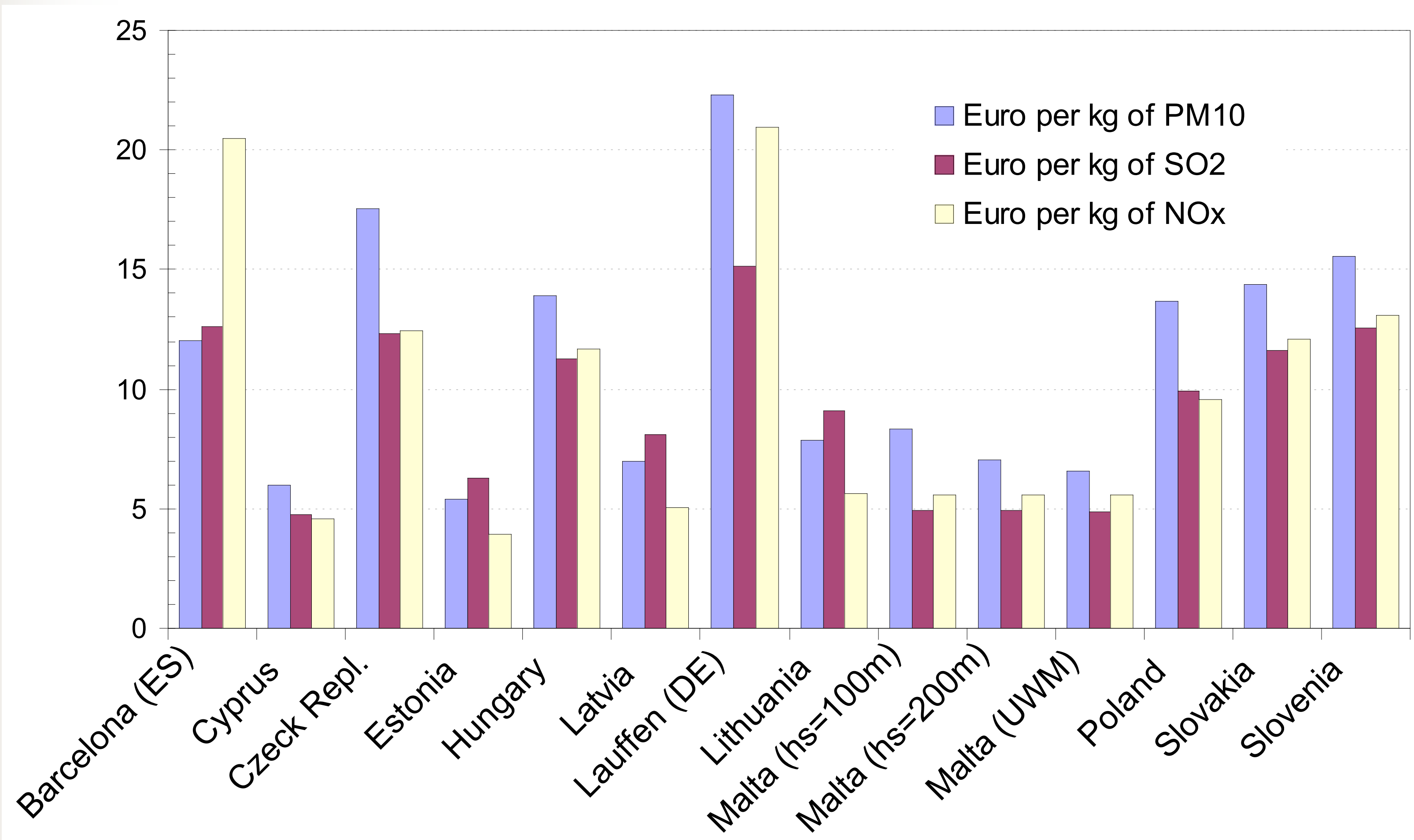
Multipliers

Pollutant	Site (rural ↔ urban)	Stack height (250m ↔ ~0m)
Primary	0.5 – 6	0.6 – 15
Aerosols	0.7 – 1.4	~ 1
Carcinogens	0.5 – 6	0.6 – 15

Dioxins include inhalation and ingestion contributions (inhalation ~ 2% total), all others inhalation only.

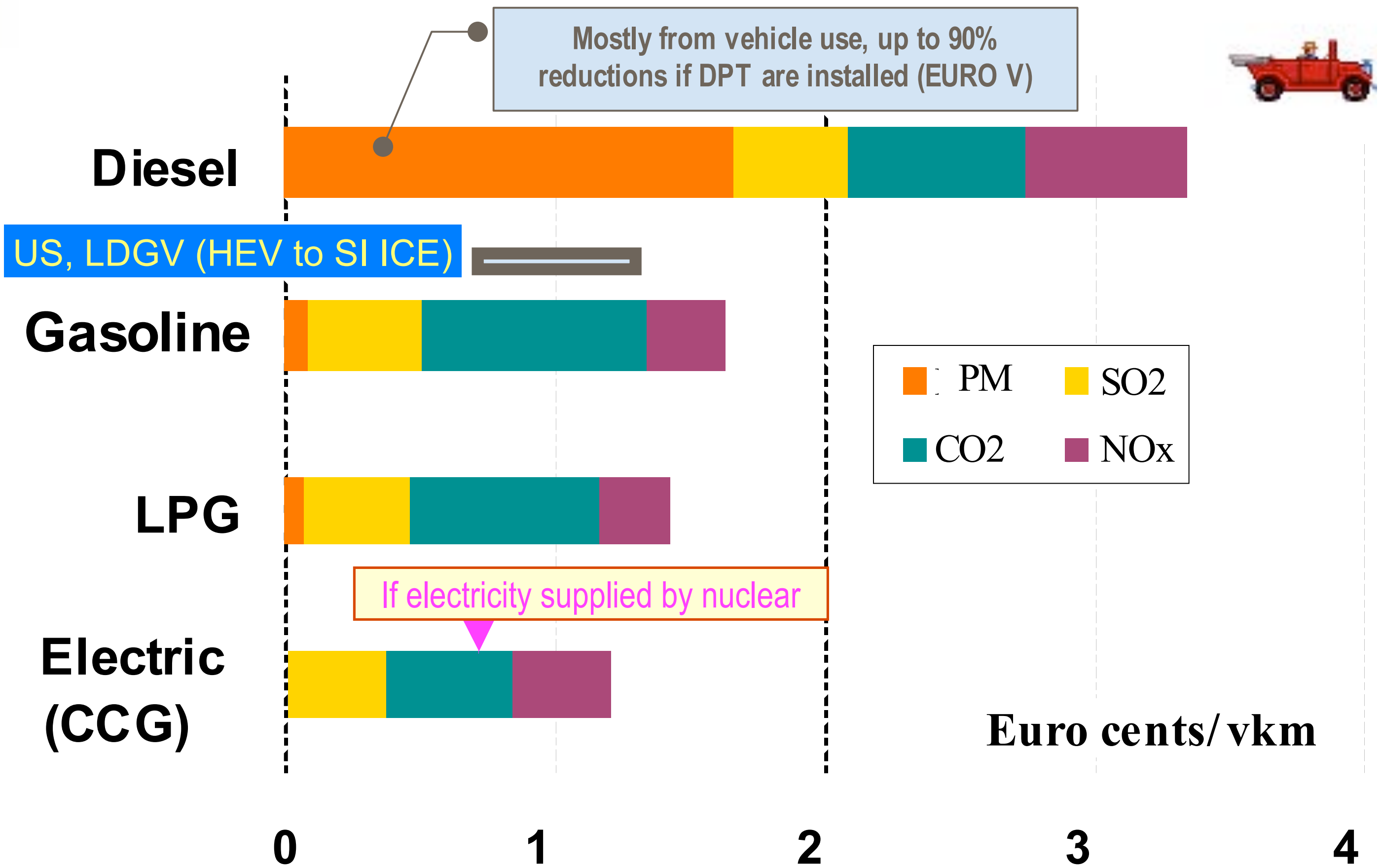
(results based on ExternE 2000 methodology)

Variability of damage cost per kg of pollutant across Europe



(results based on ExternE 2004 methodology)

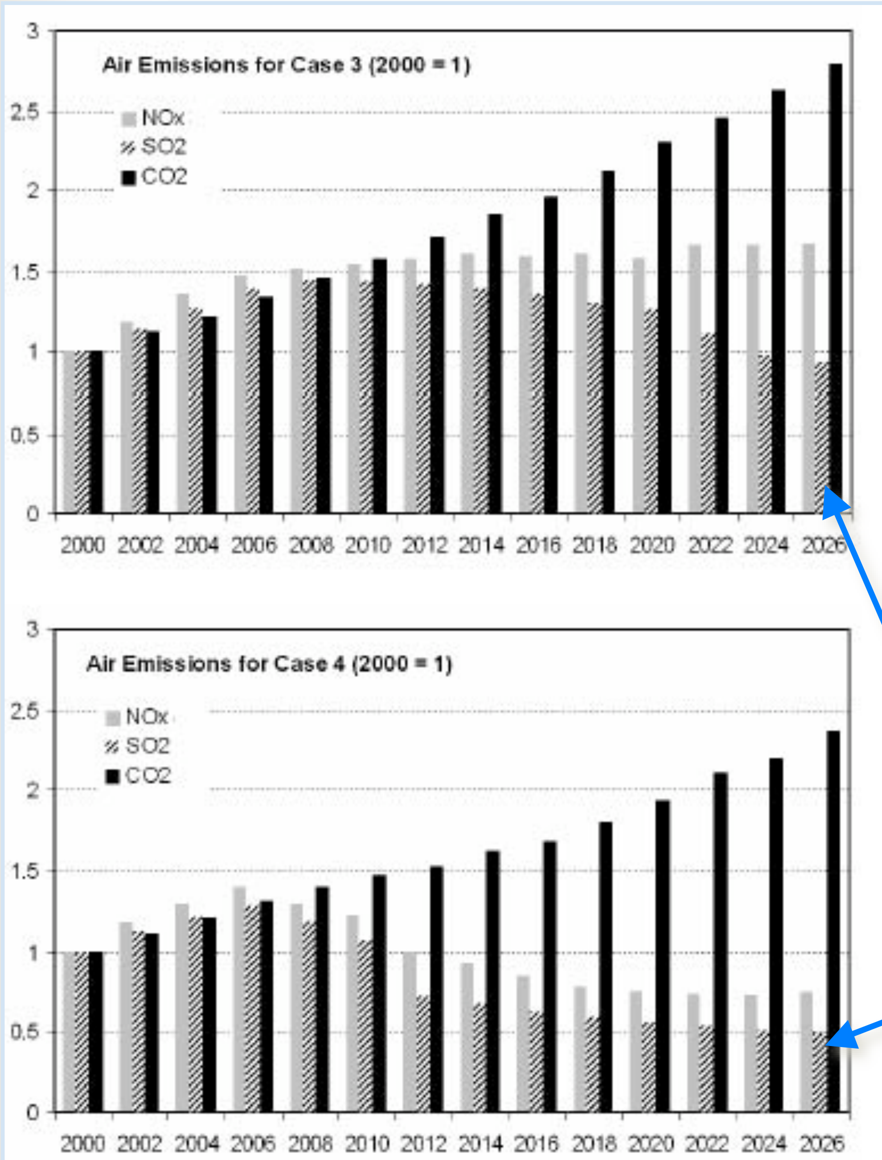
Life cycle damage costs of automotive air emissions in Europe



European fuel cost (€ cents/vkm)
Diesel fuel 3.9
Gasoline fuel 7.6

Emissions data from ExternE Transport (2000)

Damage internalization: The case study of Java Island, Indonesia



- Analysis includes supply/demand forecast (MAED), energy-economy assessment (MARKAL), and environmental impact analysis (cost adders estimated by RiskPoll).
- Social aspects have not been considered, 3rd aspect of sustainable development (may require MCDA).
- Case 3 (top graph) excludes social costs, while full cost accounting is applied to Case 4 results.
- The decrease in emissions reflects fuel switching from fossil fuels to nuclear energy and renewables.

2026 avoided emissions

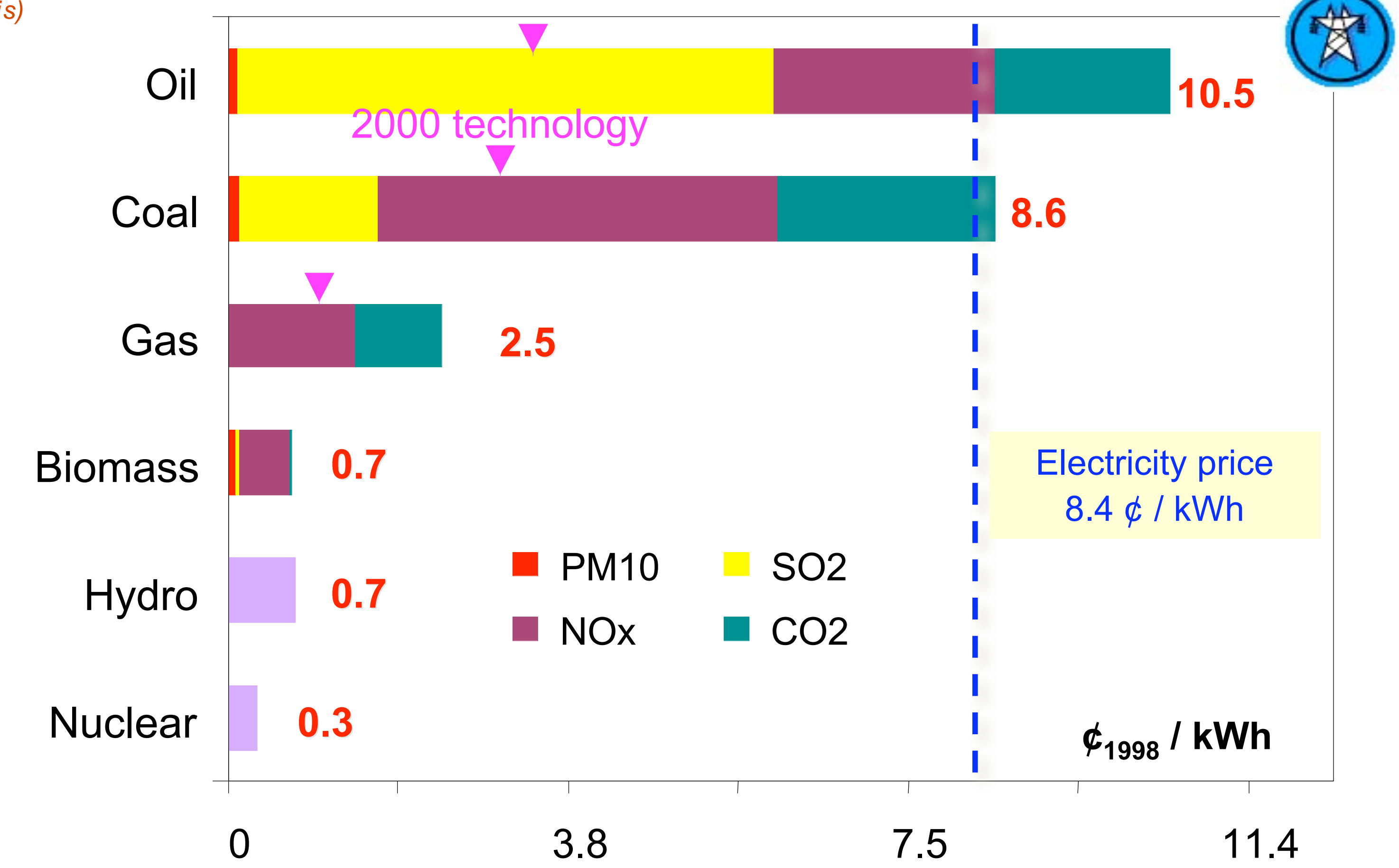
NOx – 45%

SO_2 – 55%

CO_2 – 15%

External costs of electricity generation in France

(direct emissions only, except for CO_2 emissions which are based on life-cycle analysis)



Aggregate costs (500 TWh/yr): ~ 6 billion US$ (~0.5% GDP); ~ 36,000 YOLL (Europe)

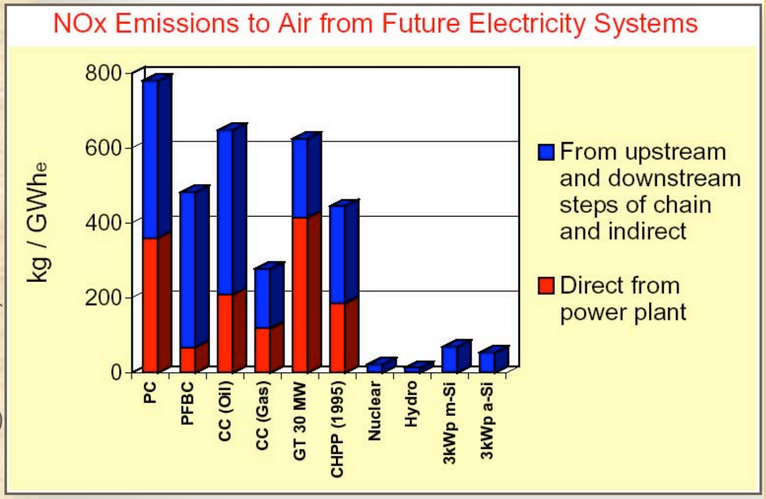
(results based on ExternE 1998 methodology)

Health costs of electricity: Input data

POWER PLANT BASE CASE CHARACTERISTICS
(SOURCE: EXTERNE 1995, VOLS. 3 AND 4)

Parameter	Coal plant	Natural gas plant
Generation capacity and Thermal efficiency	510 MW 37.5%	650 MW 51%
Load factor	0.76	0.90
Pollution abatement ESP – Electrostatic precipitators FGD – Flue gas desulfurization (Percentages = removal efficiency)	*Pulverized Coal (PC)* ESP – 99.7% FGD – 90% Low NOx burners	*Combined Cycle Gas Turbine (CCGT)* Low NOx burners
Stack height	240 m	65 m
Stack diameter	10 m	5.7 m
Exhaust flow temperature	403 K (130 °C)	378 K (105 °C)
Exhaust flow speed	9.2 m/s	14.7 m/s

Health costs of electricity: Input data (2)

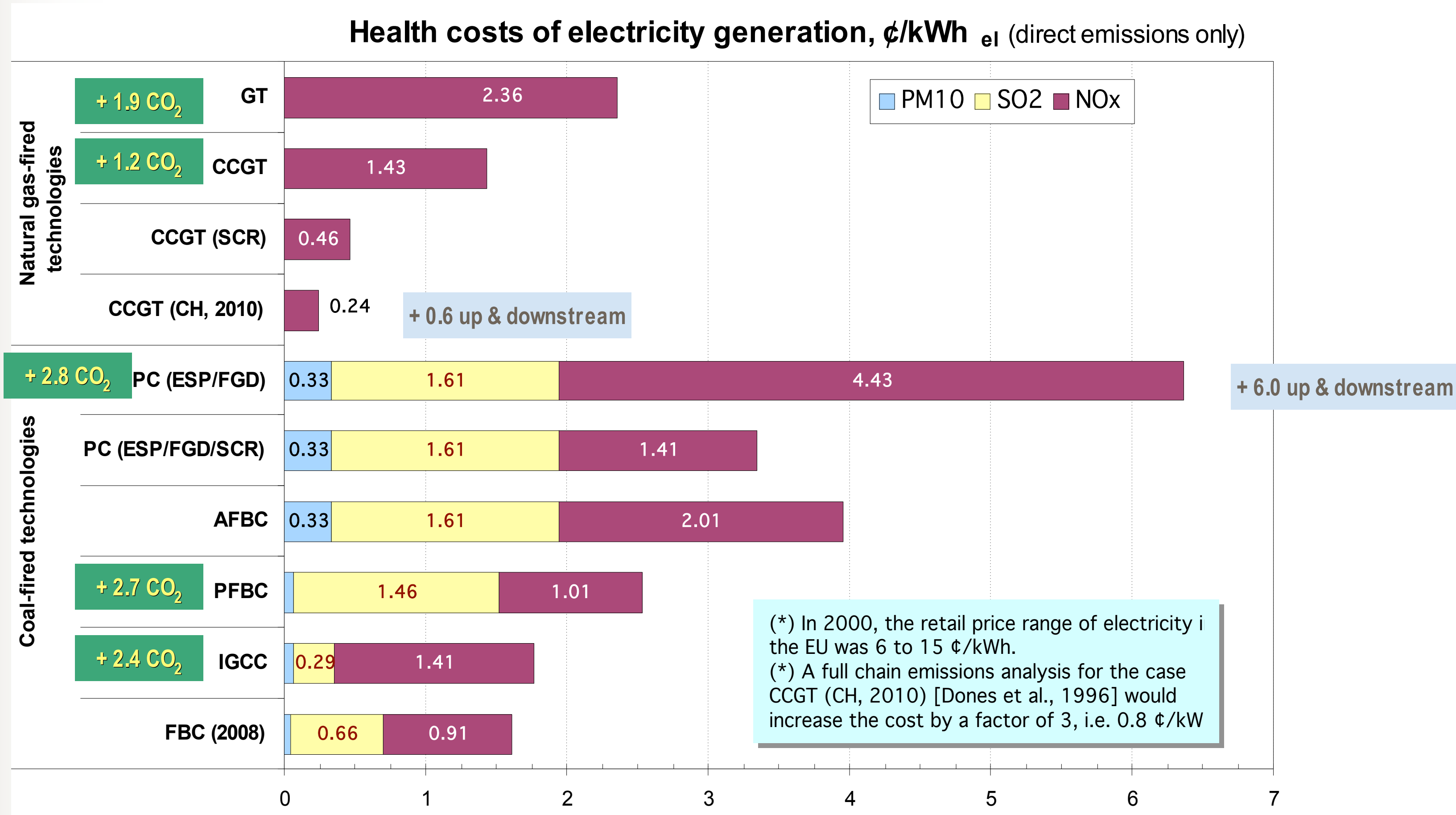


ATMOSPHERIC EMISSIONS PER UNIT OF OUTPUT ENERGY

(SOURCE: EXTERNE 1995, VOLS. 3 AND 4)

	Coal	Natural gas
Base case	*Pulverized coal*	*Combined cycle GT*
	ESP+FGD+Low NOx burners	Low NOx burners
Emission factors		
Particulates (PM_{10})	0.16 g/kWh (543 t/yr)	negligible
Sulfur dioxide (SO_2)	1.1 g/kWh (3735 t/yr)	< 0.0032 g/kWh (16.4 t/yr)
Nitrogen oxides (NOx)	2.2 g/kWh (7470 t/yr)	0.71 g/kWh (3638 t/yr)
Option #1	*Pulverized coal*	*Combined cycle GT*
(SCR – Selective Catalytic Reduction)	ESP+FGD+SCR	SCR
	Thermal efficiency 37.5%	Thermal efficiency 51%
Emission factors		
Particulates (PM_{10})	0.16 g/kWh (543 t/yr)	negligible
Sulfur dioxide (SO_2)	1.1 g/kWh (3735 t/yr)	< 0.0032 g/kWh (16.4 t/yr)
Nitrogen oxides (NOx)	0.7 g/kWh (2377 t/yr)	0.23 g/kWh (3638 t/yr)
Option #2	*Atmospheric Fluidized Bed Combustion – AFBC*	*Gas Turbine (GT) 30 MW, 0.51 load factor*
	Thermal efficiency 37%	Low NOx burners
		Thermal efficiency 31%
Emission factors		
Particulates (PM_{10})	0.16 g/kWh (543 t/yr)	negligible
Sulfur dioxide (SO_2)	1.1 g/kWh (3735 t/yr)	< 0. 0032 g/kWh (0.43 t/yr)
Nitrogen oxides (NOx)	1.0 g/kWh (3395 t/yr)	1.17 g/kWh (157 t/yr)
Option #3	*Pressurized Fluidized Bed Combustion – PFBC*	
	Thermal efficiency 41%	
Emission factors		
Particulates (PM_{10})	0.03 g/kWh (102 t/yr)	
Sulfur dioxide (SO_2)	1.0 g/kWh (3395 t/yr)	
Nitrogen oxides (NOx)	0.5 g/ kWh (1698 t/yr)	
Option #4	*Integrated Gasification Combined Cycle (IGCC)*	
	Thermal efficiency 42.5%	
Emission factors		
Particulates (PM_{10})	0.03 g/kWh (102 t/yr)	
Sulfur dioxide (SO_2)	0.2 g/kWh (679 t/yr)	
Nitrogen oxides (NOx)	0.7 g/kWh (2377 t/yr)	
Fuel properties	1.6% S; 1.3% N; 60% C; 15% ash; calorific value 24.5 MJ/kg	93% methane; 3% N and 0.3% CO_2

Health costs of electricity for a power plant in Central Europe

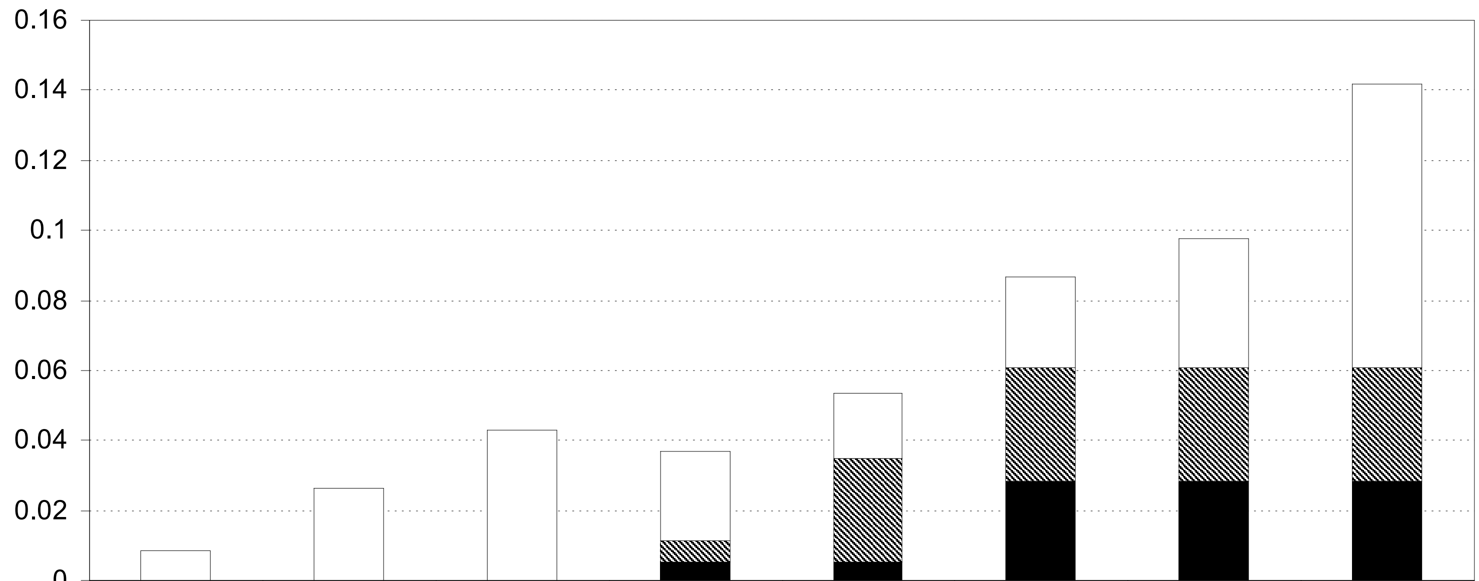


(results based on ExternE 2000 methodology)

Health costs of electricity for a power plant in South Africa

Damage costs of fossil fuel generation in ¢/kWh

(power station located near Cape Town, South Africa)



	CCGT+SCR (51%)	CCGT (51%)	GT (31%)	IGCC (42.5%)	PFBC (41%)	PC/FGD/SCR (37.5%)	AFBC (37%)	PC+FGD (37.5%)
□ NOx	0.008	0.026	0.043	0.026	0.018	0.026	0.037	0.081
▧ SO2	0.0001	0.0001	0.0001	0.006	0.030	0.033	0.033	0.033
■ Particulates	0	0	0	0.005	0.005	0.028	0.028	0.028

Damage costs are lower in South Africa by an order of magnitude compared to estimates for the same power plant in Central Europe because the population density and economic costs per health endpoint are lower in South Africa.

Cost effectiveness of retrofit options in the power industry

HEALTH COSTS

Assumptions

Retrofit details			
Wet FGD removal efficiency	95	%	(IEA Coal Research, 2001 - page 13)
Low NOx burners removal efficiency	37	%	(IEA Coal Research, 2001 - page 22)
SCR removal efficiency	80	%	(IEA Coal Research, 2001 - page 26)
Economic details			
GDP growth rate	1	% per year	
Discount rate	10	% per year	
Interest rate for levelized cost	10	% per year	
Levelized factor	0.131		
Lifetime of abatement equipment	15	years	

ABATEMENT COSTS (coal power plant)

Assumptions

Retrofit details			
Capacity (LF = 85%)	300	MW	
Wet FGD removal efficiency	95	%	(IEA Coal Research, 2001 - page 13)
Low NOx burners removal efficiency	37	%	(IEA Coal Research, 2001 - page 22)
SCR removal efficiency	80	%	(IEA Coal Research, 2001 - page 26)
Economic details			
Wet FGD (LSFO capital costs)	120	$/kW	(IEA Coal Research, 2001 - page 12, can vary by 2X)
Wet FGD (LSFO, low S operating costs)	0.695	$/MWh	(IEA Coal Research, 2001 - Table 5, page 15)
Low NOx burners (capital cost)	14	$/kW	(IEA Coal Research, 2001 - page 22)
Labor cost for Low NOx burners	0.0075	mills/kWh	(IEA Coal Research, 2001 - 1st Paragraph, p. 23)
SCR (capital costs)	65	$/kW	(IEA Coal Research, 2001 - Table 14, page 26)
SCR (operating costs)	260	$/tNOx removed	(IEA Coal Research, 2001 - Table 14, page 26)
Labor/maintenance cost growth rate	2	% per year	
Discount rate	10	% per year	
Interest rate for levelized cost	10	% per year	
Levelized factor	0.131		
Lifetime of abatement equipment	15	years	

Cost effectiveness of retrofit options in the power industry (2)

Bituminous coal:
1% S, LHV - 25.2 MJ/kg

Uncontrolled emissions (g/kWh):
SO_2 - 7.145; NOx - 4.136

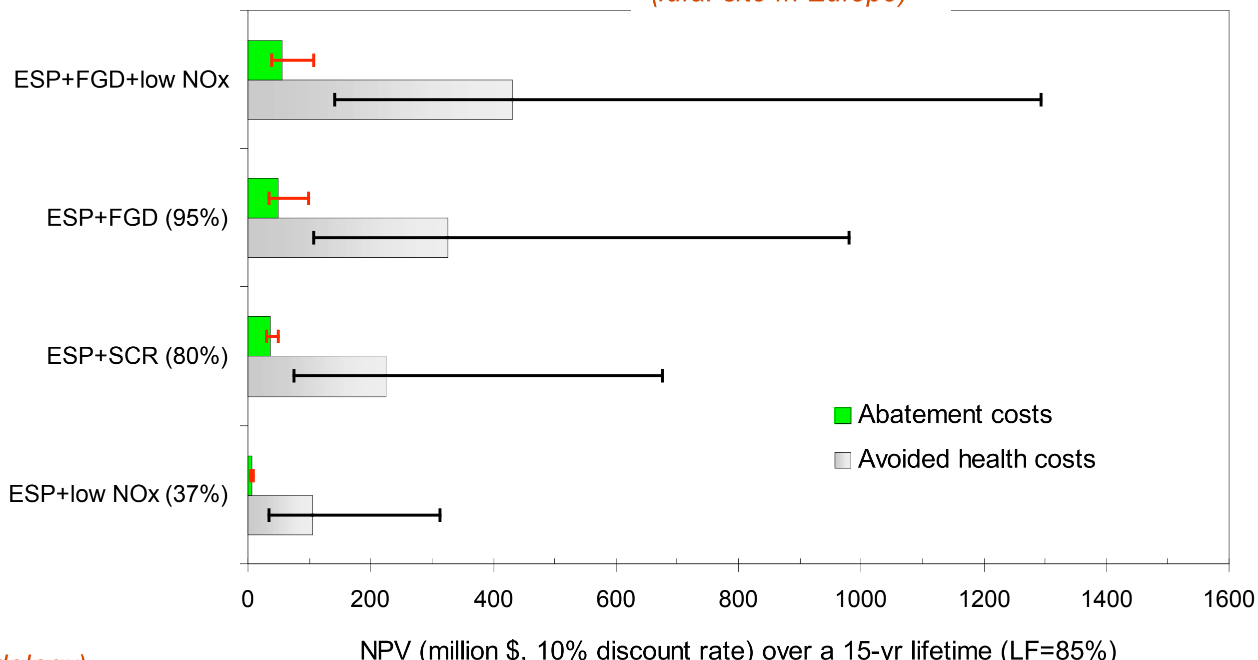
Health costs ($/kg):
SO_2 - 2.69; NOx - 3.79
(ONLY morbidity impacts)

Horizontal lines identify cost range estimates. For health costs, ranges correspond to 1 standard deviation, while for abatement investments, upper and lower bound values are based on data reported in the publication IEA Coal Research, Air pollution control costs for coal-fired power stations (October 2001).

(Avoided Health - Abatement Cost) as NPV cost (million $)
(health damages include only morbidity costs)

Discount rate (%)	ESP+FGD+low NOx	ESP+FGD (95%)	ESP+SCR (80%)	ESP+low NOx (37%)
0	844	638	436	207
5	532	395	267	137
10	375	277	188	98
15	276	202	138	74

Benefit-Cost Analysis for a 300 MW Pulverized Coal Plant
(rural site in Europe)



(results based on ExternE 2000 methodology)

Cost effectiveness of retrofit options in the power industry (3)

Bituminous coal:
1% S, LHV - 25.2 MJ/kg

Uncontrolled emissions (g/kWh):
SO_2 - 7.145; NOx - 4.136

Health costs ($/kg):
SO_2 – 9.27; NOx - 13.08
(mortality & morbidity impacts)

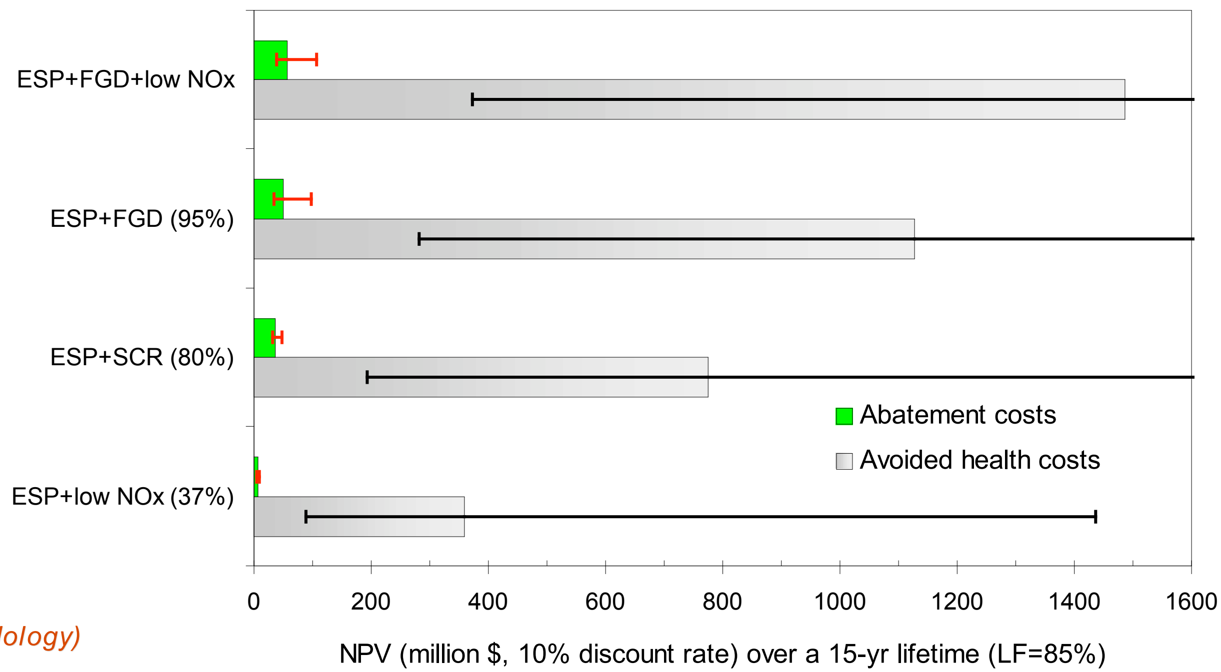
Horizontal lines identify cost range estimates. For health costs, ranges correspond to 1 standard deviation, while for abatement investments, upper and lower bound values are based on data reported in the publication IEA Coal Research, Air pollution control costs for coal-fired power stations (October 2001).

(results based on ExternE 2000 methodology)

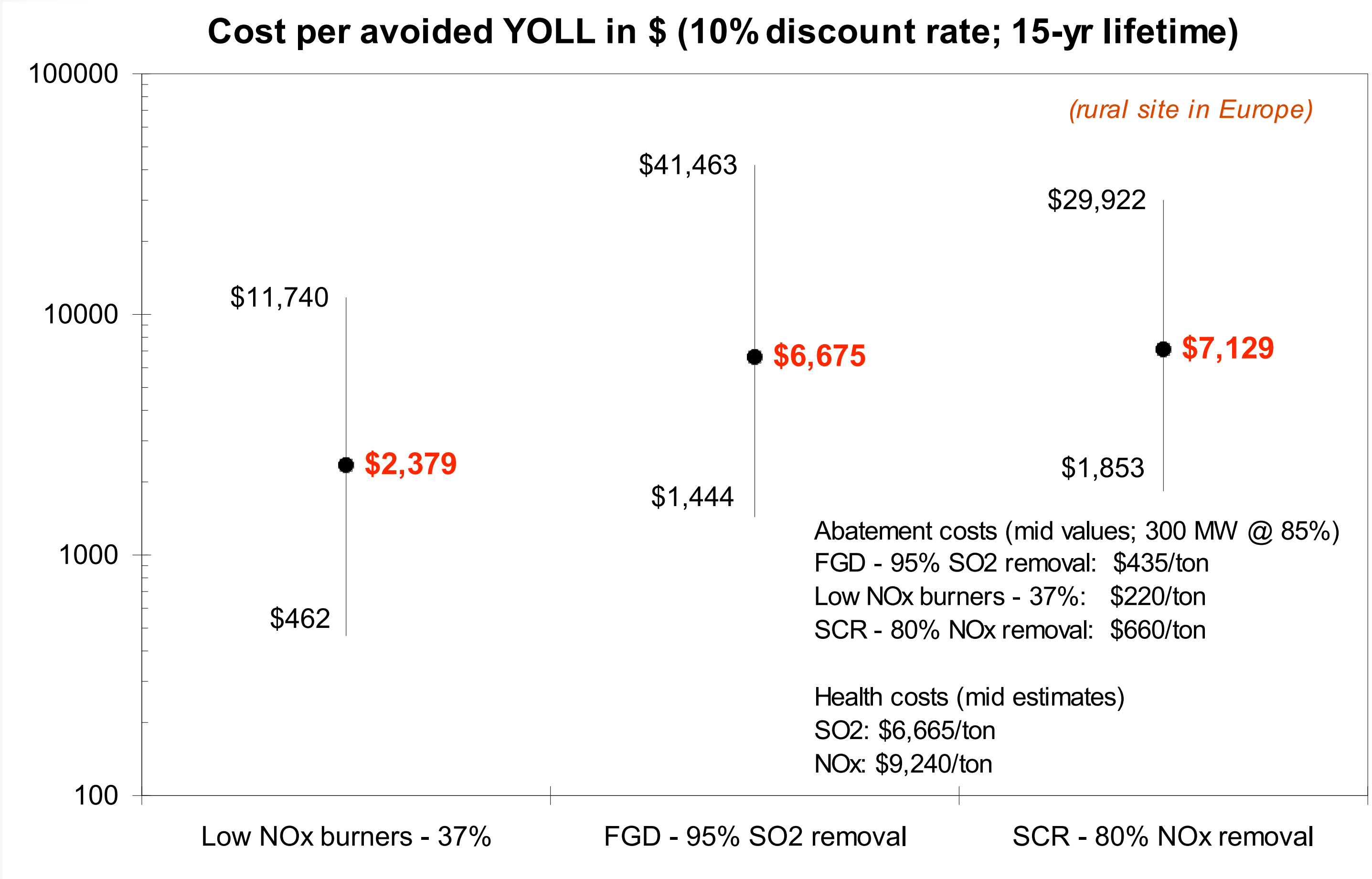
Net benefit as NPV cost (million $)
(health damages include both mortality and morbidity costs)

Discount rate (%)	ESP+FGD+low NOx	ESP+FGD (95%)	ESP+SCR (80%)	ESP+low NOx (37%)
0	2912	2199	1504	713
2	2479	1872	1280	608
4	2132	1608	1101	523
6	1850	1395	956	455
8	1620	1221	837	399
10	1430	1077	739	353
12	1273	958	657	315
15	1082	813	559	269

Benefit-Cost Analysis for a 300 MW Pulverized Coal Plant
(rural site in Europe)

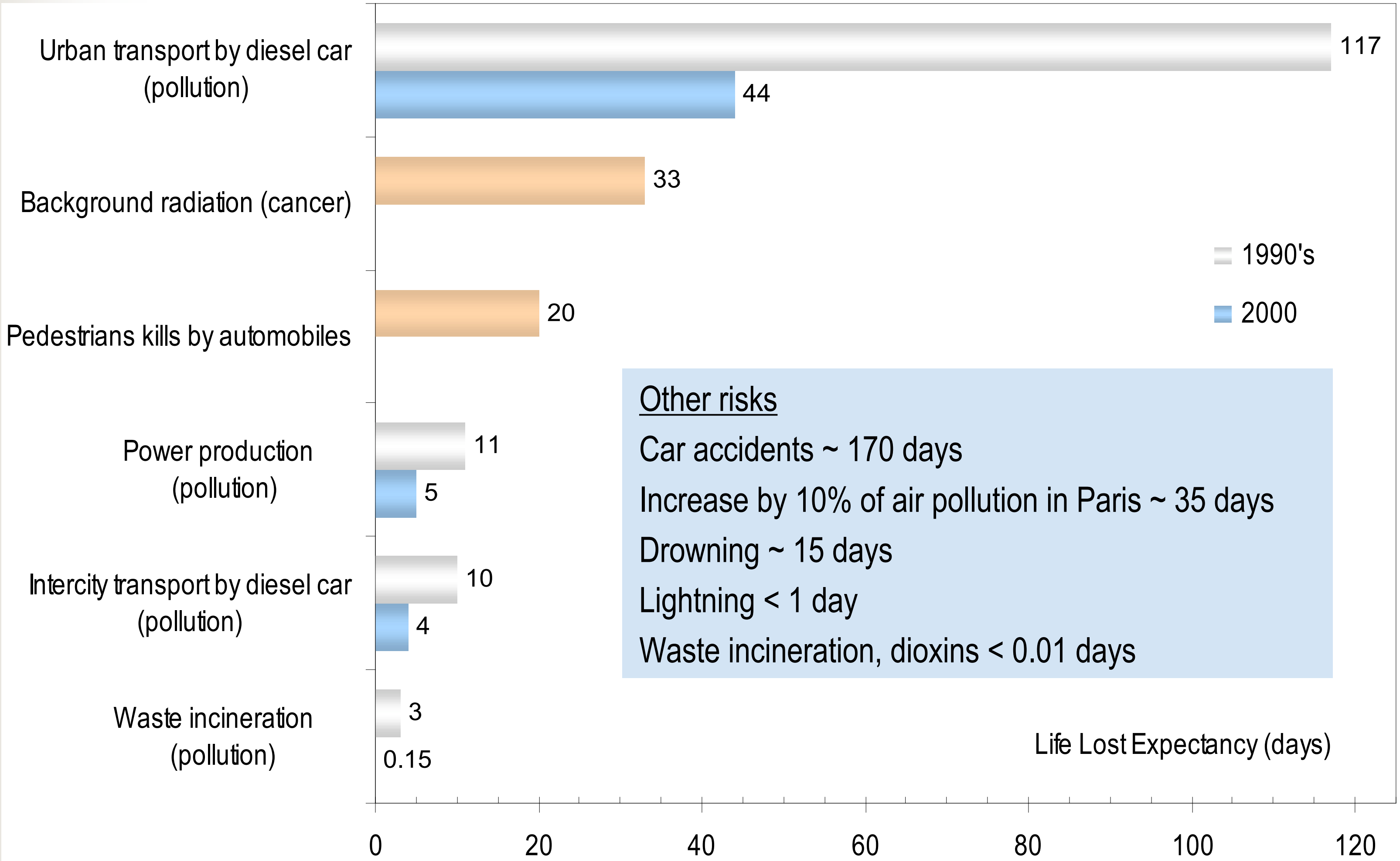


Cost effectiveness of retrofit options in the power industry (4)



(results based on ExternE 2000 methodology)

Individual lifetime risks for French population



RiskPoll multimedia assessment

See references for further reading

Toxic metals multimedia assessment

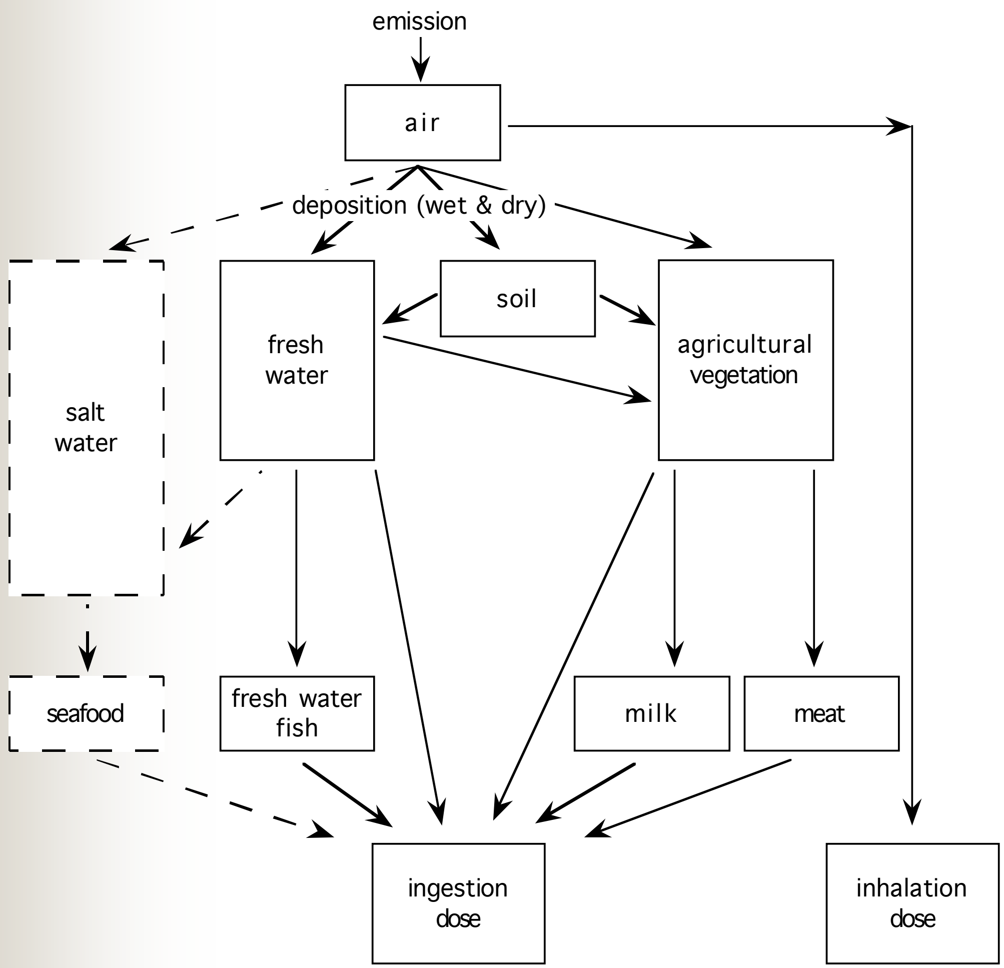
- Compared to more traditional risk assessments that calculate site specific results or impacts to critical groups based on a "worst case" assessment, the intended purpose of this model is to inform decision-takers on the environmental benefits of reducing toxic metal emissions that reflect "collective" preferences.

- The goal is to calculate "expectation" values of the health impacts of toxic metal emissions for typical sites and conditions. For ex.,
  - Population-total or collective dose over a specified time interval (cutoff time),
  - Intake fractions via inhalation and ingestion routes of exposure,
  - Physical impacts (cancers, IQ decrement),
  - Damage costs (total and per unit emission).

- Toxic metals included in current version: As, Cd, Cr, Hg, Ni and Pb.

Toxic metals multimedia assessment (2)

q Exposure pathways for health impacts of airborne emissions



– Inhalation pathway

– Ingestion of food products
  - meat,
  - milk, and
  - freshwater-fish

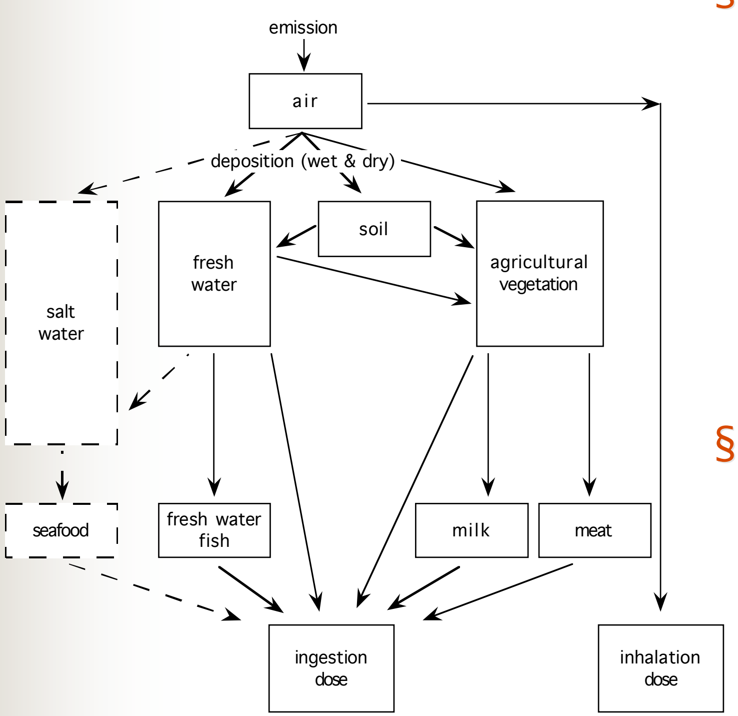
– Dose from seafood is not yet included; this pathway is potentially significant because of bioaccumulation of pollutants and because most fish in the human diet comes from the ocean rather than freshwater sources (important for Hg).

– Dermal contact exposure is negligible

– Extension of the model to assess doses from “direct” emissions to soil or water compartments is straightforward; the analysis begins at the “soil” or “water” box and the deposition flux is replaced with the appropriate discharge rate.

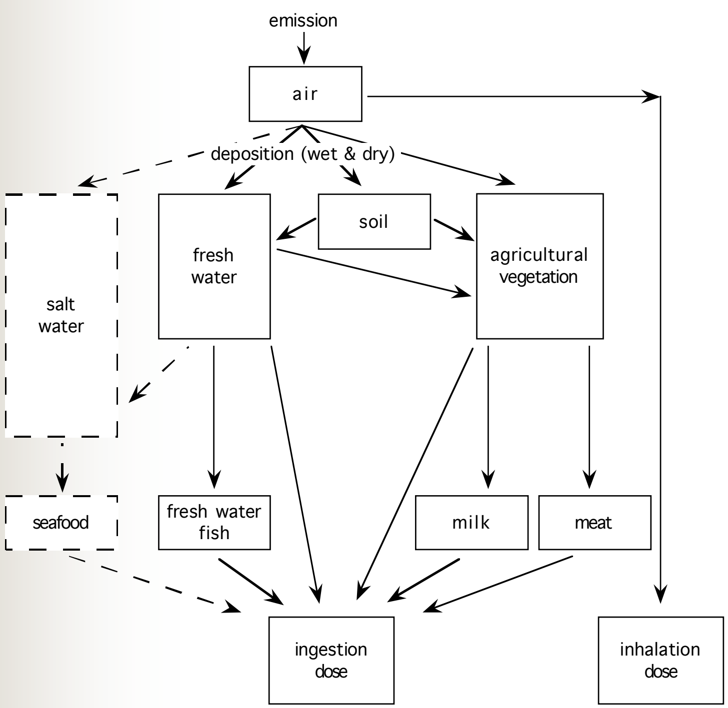
Toxic metals multimedia assessment (3)

Pollutant concentration in food



- <u>Soil calculations</u>
  - Three pathways are considered: cropland, pasture and direct soil ingestion by animals.
  - Mass inflow from atmospheric deposition.
  - Mass outflow characterized by the soil loss constant k_{soil}, which takes into account losses due to leaching, runoff and erosion (exchanges with deep soil layers are ignored).
- <u>Water calculations</u>
  - Concentrations due to flow rate of the pollutant through rivers and lakes of the watershed from direct deposition and soil losses.
  - No filtration for crop irrigation; for drinking water, dissolved water phase concentration is used.
- <u>Assimilation into food and feedstock products</u>
  - Crops – foliar absorption and root uptake
  - Animals – water and feedstook consumption
  - Food contamination (meat, milk, freshwater fish) is based on bio-transfer factors

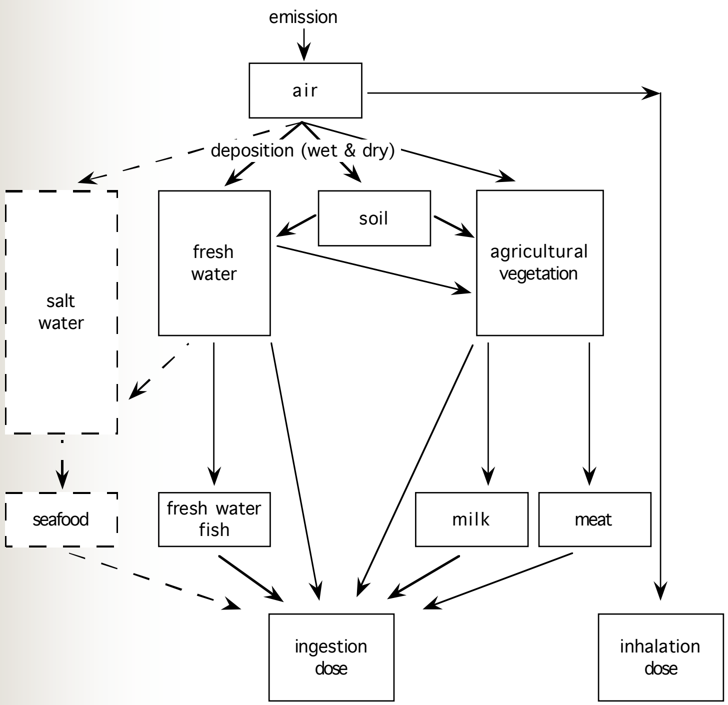
Toxic metals multimedia assessment (4)



- Compared to other toxic metals, Hg analysis is the most uncertain because of the complexities in modeling and chemical transformation.
- In the atmosphere, Hg(0) exists as metallic vapor (residence 1-2 yrs; deposition vel. ~ 0.023 cm/s).
- Hg(0) → Reactive Gaseous Mercury (RGM), approximately 1-3%; RGM deposits quickly, mostly by wet deposition.
- In water bodies, mercury is transformed into methlymercury (MeHg) by sulfate reducing bacteria. Usually, 90% of mercury lies in bottom sediment as mercuric sulfide. MeHg levels are generally in the range 1-10%, but may be higher.
- In the present assessment of the inhalation dose, mercury is treated as metallic vapor. For the ingested dose, mercury is considered as MeHg.
- Transfer factors and bioconcentration coefficients are based on MeHg.

Toxic metals multimedia assessment (5)

- Dose and impact calculations are based on the UWM approach



- Inhalation
  - UWM has been validated by comparisons with detailed model results for sites in EU, Eastern Europe, China, Thailand, Argentina, Brazil, Paraguay and the USA.
  - Collective dose rate

$$D_{inhalation} = \dot{V}_{inhalation}\ \rho\ \frac{\dot{m}}{v_{dep}}$$

  - Collective impact rate

$$I_{inhalation} = s_{CRF}\ \rho\ \frac{\dot{m}}{v_{dep}}$$

$V_{inhalation}$ = mean annual breathing rate

r = population density

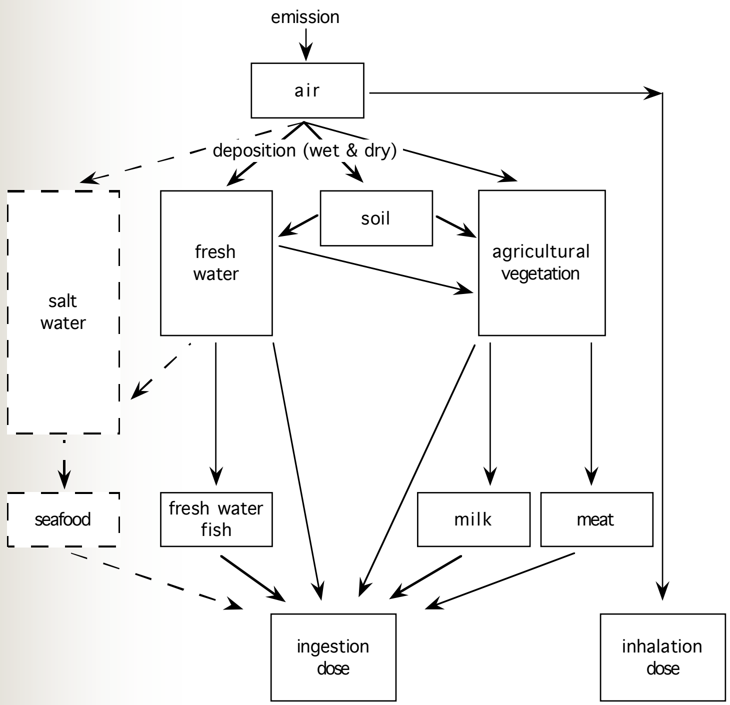
m = pollutant emission rate to air

v_{dep} = deposition velocity (dry + wet)

s_{CRF} = Concentration Response Function slope

Toxic metals multimedia assessment (6)

- Dose and impact calculations are based on the UWM approach (cont.)



- Ingestion
  - UWM is anticipated to be even better because food is transported over large distances between different areas where food is grown.
  - Collective dose and impact rates

$$D_{ingestion} = \rho \frac{\dot{m}}{v_{dep}} \sum_{p} X_{food,p}\, Q_{food,p}$$

$$I_{ingestion} = s_{DRF}\, \rho \frac{\dot{m}}{v_{dep}} \sum_{p} X_{food,p}\, Q_{food,p}$$

$$X_{food,p} = \frac{C_{food,p}}{C_{air}} \quad \text{air} \rightarrow \text{food transfer factor}$$

$Q_{food,\,p}$ = annual food consumption of product p

C = concentration

r = population density

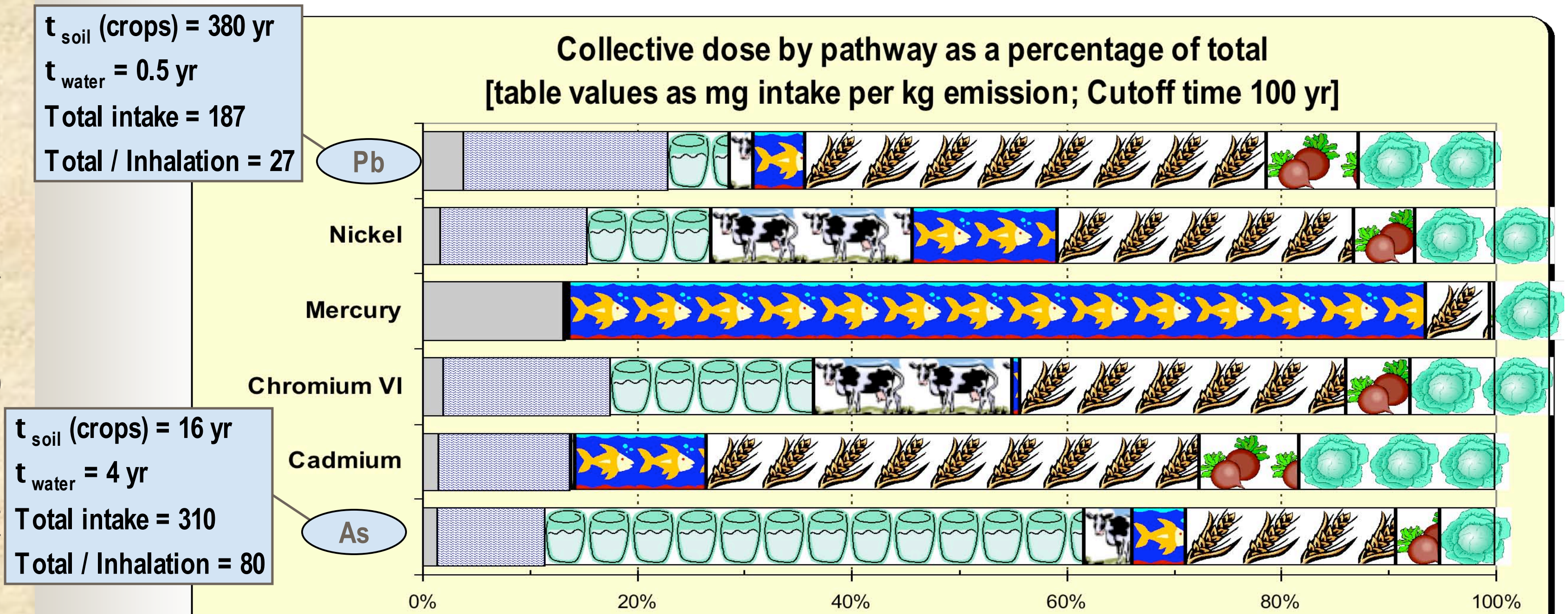
m = pollutant emission rate to air

v_{dep} = deposition velocity (dry + wet)

s_{DRF} = Dose Response Function slope

Toxic metals multimedia assessment (7)

- Impact of toxic metal emissions for central European conditions



	Arsenic	Cadmium	Chromium VI	Mercury	Nickel	Lead
Green vegetables	16.2	47.5	15.9	0.3	17.7	24.0
Root vegetables	12.4	24.1	12.0	0.7	13.1	16.0
Grains	60.8	119.5	60.4	10.1	64.4	80.4
Freshwater fish	15.6	31.7	1.6	134.9	31.6	9.0
Cattle meat	13.8	1.4	36.8	0.3	43.9	4.1
Cattle milk	156.2	0.3	38.0	0.4	27.2	10.8
Water	31.1	31.7	31.0	0.3	31.5	35.5
Inhalation	3.9	3.9	3.9	22.0	3.9	7.1

Toxic metals multimedia assessment (8)

- Impact of toxic metal emissions for central European conditions (cont.)
  - Collective doses, impacts and social costs (2 M€ per cancer; 3000 € per IQ point)

Parameter	Description	Units	Arsenic	Cadmium	Chromium VI	Nickel	Lead
INHALATION pathway							
Vdep	Total deposition velocity (dry+wet)	cm/s	0.49	0.49	0.49	0.49	0.27
s_{CR}	Slope concentration response function	cancers/(pers.yr.kg/m3)	6.14E+04	2.57E+04	1.71E+05	3.43E+03	
D_inhal	**Collective inhalation dose**	**kg/yr**	**3.89E-03**	**3.89E-03**	**3.89E-03**	**3.89E-03**	**7.06E-03**
I_inhal	**Collective impact**	**cancers/yr**	**3.18E-02**	**1.33E-02**	**8.85E-02**	**1.78E-03**	
Cost_inhal	**Social cost from inhalation**	**€ per yr**	**6.36E+04**	**2.66E+04**	**1.77E+05**	**3.55E+03**	
Iu_inhal	**Unit impact from inhalation**	**cancers per kg**	**3.18E-05**	**1.33E-05**	**8.85E-05**	**1.78E-06**	
Uv_inhal	**Unit cost from inhalation**	**€ per kg**	**63.6**	**26.6**	**177.1**	**3.6**	
INGESTION pathway							
s_{DR}	Slope dose response function	cancers/kg_absorbed	1.07				
s_{DR_Pb}	Slope dose response function for Pb	IQ_points/kg_absorbed					3291
D_food	**Collective ingestion dose**	**kg/yr**	**3.06E-01**	**2.56E-01**	**1.96E-01**	**2.29E-01**	**1.80E-01**
I_food	**Collective impact**	**cancers/yr**	**3.28E-01**				
I_food_Pb	**Collective impact for Pb**	**IQ_points/yr**					**5.92E+02**
Cost_food	**Social cost from ingestion**	**€ per yr**	**6.55E+05**				**1.78E+06**
Iu_food	**Unit impact from ingestion**	**cancers per kg**	**3.28E-04**				
Iu_food_Pb	**Unit impact from ingestion of Pb**	**IQ points per kg**					**0.592**
Uv_food	**Unit cost from ingestion**	**€ per kg**	**655.4**				**1775.6**
TOTAL results							
	Collective dose	[illegible]	[illegible]	[illegible]	**2.00E-01**	**2.33E-01**	**1.87E-01**
	Collective impact	[illegible]	[illegible]	[illegible]	**8.85E-02**	**1.78E-03**	
	Collective impact of Pb	**IQ_points/yr**					**5.92E+02**
	Annual cost	**€ per yr**	**7.19E+05**	**2.66E+04**	**1.77E+05**	**3.55E+03**	**1.78E+06**
	Unit impact	**cancers per kg**	**3.59E-04**	**1.33E-05**	**8.85E-05**	**1.78E-06**	
	Unit impact of Pb	**IQ points per kg**					**5.92E-01**
	Unit cost	**€ per kg**	**718.9**	**26.6**	**177.1**	**3.6**	**1775.6**

Cancers per 1000 tons of emission

359   13   9   2

Toxic metals multimedia assessment (9)

- Impact of toxic metal emissions for central European conditions (cont.)
  - Collective doses, impacts and social costs (2 M€ per cancer; 3000 € per IQ point)

Parameter	Description	Units	Arsenic	Cadmium	Chromium VI	Nickel	Lead
INHALATION pathway							
Vdep	Total deposition velocity (dry+wet)	cm/s	0.49	0.49	0.49	0.49	0.27
s_{CR}	Slope concentration response function	cancers/(pers.yr.kg/m3)	6.14E+04	2.57E+04	1.71E+05	3.43E+03	
D_inhal	**Collective inhalation dose**	**kg/yr**	**3.89E-03**	**3.89E-03**	**3.89E-03**	**3.89E-03**	**7.06E-03**
I_inhal	**Collective impact**	**cancers/yr**	**3.18E-02**	**1.33E-02**	**8.85E-02**	**1.78E-03**	
Cost_inhal	**Social cost from inhalation**	**€ per yr**	**6.36E+04**	**2.66E+04**	**1.77E+05**	**3.55E+03**	
Iu_inhal	**Unit impact from inhalation**	**cancers per kg**	**3.18E-05**	**1.33E-05**	**8.85E-05**	**1.78E-06**	
Uv_inhal	**Unit cost from inhalation**	**€ per kg**	**63.6**	**26.6**	**177.1**	**3.6**	
INGESTION pathway							
s_{DR}	Slope dose response function	cancers/kg_absorbed	1.07				
s_{DR_Pb}	Slope dose response function for Pb	IQ_points/kg_absorbed					3291
D_food	**Collective ingestion dose**	**kg/yr**	**3.06E-01**	**2.56E-01**	**1.96E-01**	**2.29E-01**	**1.80E-01**
I_food	**Collective impact**	**cancers/yr**	**3.28E-01**				
I_food_Pb	**Collective impact for Pb**	**IQ_points/yr**					**5.92E+02**
Cost_food	**Social cost from ingestion**	**€ per yr**	**6.55E+05**				**1.78E+06**
Iu_food	**Unit impact from ingestion**	**cancers per kg**	**3.28E-04**				
Iu_food_Pb	**Unit impact from ingestion of Pb**	**IQ points per kg**					**0.592**
Uv_food	**Unit cost from ingestion**	**€ per kg**	**655.4**				**1775.6**
TOTAL results							
	Collective dose	[illegible]	[illegible]	[illegible]	**2.00E-01**	**2.33E-01**	**1.87E-01**
	Collective impact	[illegible]	[illegible]	[illegible]	**8.85E-02**	**1.78E-03**	
	Collective impact of [illegible]	[illegible]	[illegible]	[illegible]			**5.92E+02**
	Annual cost	**€ per yr**	**7.19E+05**	**2.66E+04**	**1.77E+05**	**3.55E+03**	**1.78E+06**
	Unit impact	**cancers per kg**	**3.59E-04**	**1.33E-05**	**8.85E-05**	**1.78E-06**	
	Unit impact of Pb	**IQ points per kg**					**5.92E-01**
	Unit cost	**€ per kg**	**718.9**	**26.6**	**177.1**	**3.6**	**1775.6**

Unit Costs € per kg (typical emissions)

719 27 177 4 1776

Compare with PM_{10} = 16 €/kg

Toxic metals multimedia assessment (10)

- Impact of toxic metal emissions for central European conditions (cont.)
  - Collective doses, impacts and social costs (2 M€ per cancer; 3000 € per IQ point)

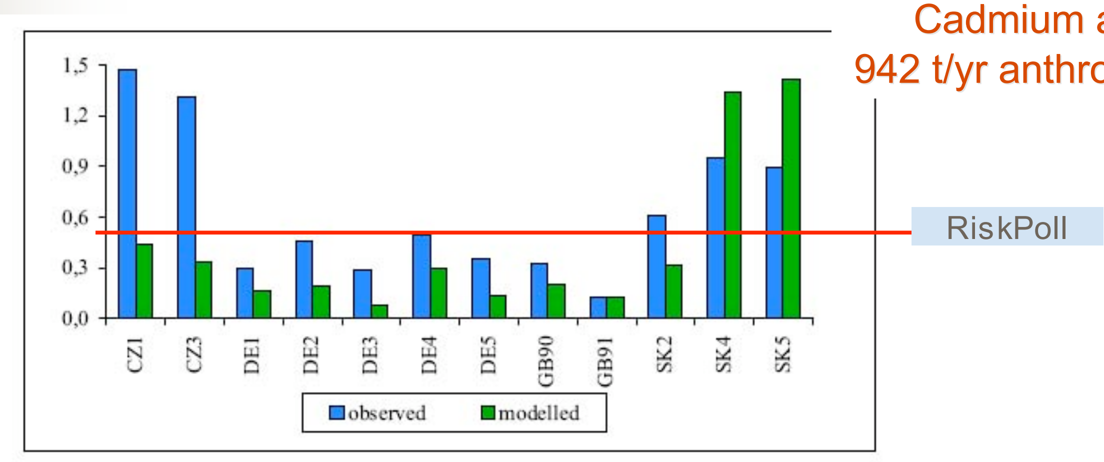
Parameter	Description	Units	Arsenic	Cadmium	Chromium VI	Nickel	Lead
INHALATION pathway							
Vdep	Total deposition velocity (dry+wet)	cm/s	0.49	0.49	0.49	0.49	0.27
s_{CR}	Slope concentration response function	cancers/(pers.yr.kg/m3)	6.14E+04	2.57E+04	1.71E+05	3.43E+03	
D_inhal	Collective inhalation dose	kg/yr	3.89E-03	3.89E-03	3.89E-03	3.89E-03	7.06E-03
I_inhal	Collective impact	cancers/yr	3.18E-02	1.33E-02	8.85E-02	1.78E-03	
Cost_inhal	Social cost from inhalation	€ per yr	6.36E+04	2.66E+04	1.77E+05	3.55E+03	
Iu_inhal	Unit impact from inhalation	cancers per kg	3.18E-05	1.33E-05	8.85E-05	1.78E-06	
Uv_inhal	Unit cost from inhalation	€ per kg	63.6	26.6	177.1	3.6	
INGESTION pathway							
s_{DR}	Slope dose response function	cancers/kg_absorbed	1.07				
s_{DR_Pb}	Slope dose response function for Pb	IQ_points/kg_absorbed					3291
D_food	Collective ingestion dose	kg/yr	3.06E-01	2.56E-01	1.96E-01	2.29E-01	1.80E-01
I_food	Collective impact	cancers/yr	3.28E-01				
I_food_Pb	Collective impact for Pb	IQ_points/yr					5.92E+02
Cost_food	Social cost from ingestion	€ per yr	6.55E+05				1.78E+06
Iu_food	Unit impact from ingestion	cancers per kg	3.28E-04				
Iu_food_Pb	Unit impact from ingestion of Pb	IQ points per kg					0.592
Uv_food	Unit cost from ingestion	€ per kg	655.4				1775.6
TOTAL results							
	Collective dose						1.87E-01
	Collective impact						
	Collective impact of [illegible]						5.92E+02
	Annual cost	€ per yr	[illegible]	[illegible]	[illegible]	[illegible]	1.78E+06
	Unit impact	cancers per kg	3.59E-04	1.33E-05	8.85E-05	1.78E-06	
	Unit impact of Pb	IQ points per kg					5.92E-01
	Unit cost	€ per kg	718.9	26.6	177.1	3.6	1775.6

Residual cost of Pb emissions from unleaded gasoline

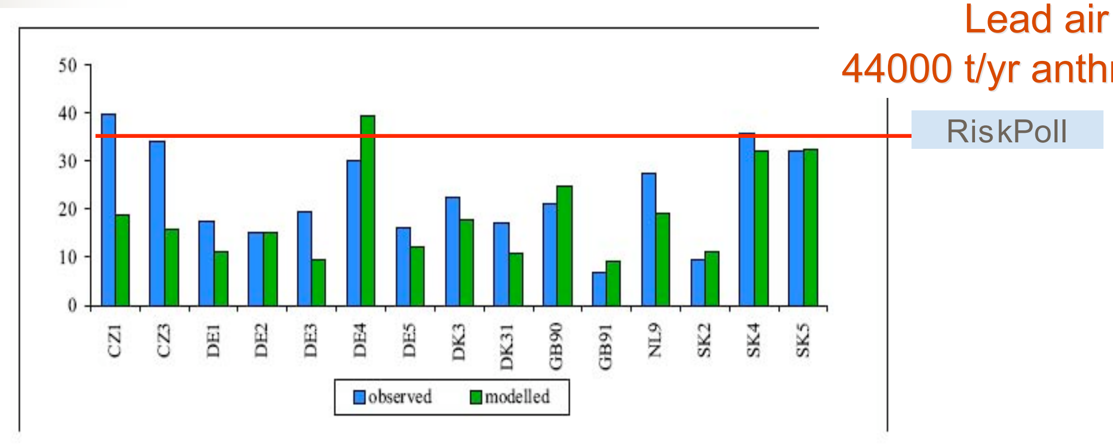
EU limit is 5 mg/L → 1776 €/kg ×5 mg/L ~ 0.01 €/L (~1% of fuel cost)

Cd & Pb assessment – RiskPoll vs. European analysis by EMEP*

Cadmium air concentrations (ng/m^3)
942 t/yr anthropogenic & natural emissions



Lead air concentrations (ng/m^3)
44000 t/yr anthropogenic & natural emissions



** Preliminary modeling and mapping of critical loads of Cd and Pb in Europe (2004), EMEP Meteorological Synthesizing Centre East, http://www.msceast.org/hms/emissions.html*

Hg multimedia assessment – RiskPoll vs. US-ATSDR analysis

Pathway	USA (ATSDR, Mar 99) ng_{Hg} / (pers-day)	RiskPoll (collective dose) mg_{Hg} / $kg_{Hg\ emission}$ τ_{cut} = 30 year	τ_{cut} = 100 year
Food			
Meat/milk		0.3	0.7
Vegetables & fruits		3.4	11
Freshwater fish	1100	104	180
Marine fish	2400	226	391
Total	*3500*	*333*	*582*
Water	8	0.15	0.3
Air	210	22	22
Pathway exposure ratios			
Crops to food	negligible	1%	2%
Freshwater fish to water	138	693	600
Freshwater fish to air	5.2	4.7	8.2
Marine fish to air	11.4	10.3	17.8

$C_{air,Hg}$ 8 to 13 ng/m^3

$C_{air,Hg}$ 3.3 to 5 ng/m^3

< Input data >

a) USA Hg air concentration in ng/m^3: 10 to 20 (urban) and 6 (rural)

b) USA fish consumption in kg/(pers-yr): 4 (freshwater) and 6.9 (marine)

c) US FDA estimate a dose of 3500 ng/(pers-day) from fish consumption; (assume Hg concentration is 125% higher in marine fish)

d) τ_{cut} = analysis cutoff time

e) RiskPoll marine fish dose has been estimates as 2.17 x freshwater dose

Uncertainty of damage costs

See references for further reading

Uncertainty of Results

- Uncertainty vs. Variability (both can cause estimates to change)
  - Uncertainty – insufficient knowledge at the present time
  - Variability – variations due to source parameters, dispersion characteristics, etc.
- Sources of uncertainty
  - Data uncertainty
    (e.g., slope of ERF, unit costs, deposition velocity, etc.)
  - Model uncertainty
    (e.g., causal links between pollutant and health impact, shape of ERF, choice of models for atmospheric dispersion and chemistry, etc.)
  - Uncertainty about policy and ethical choices, and the future
    (e.g., choice of discount rate, VSL, the potential for reducing crop losses by development of more resistant species, the potential of medical advances, etc.)
  - Idiosynchrosies of the analyst
    (e.g., human error, choice of ERF, interpretation of the existing information, etc.)

Uncertainty of Results (2)

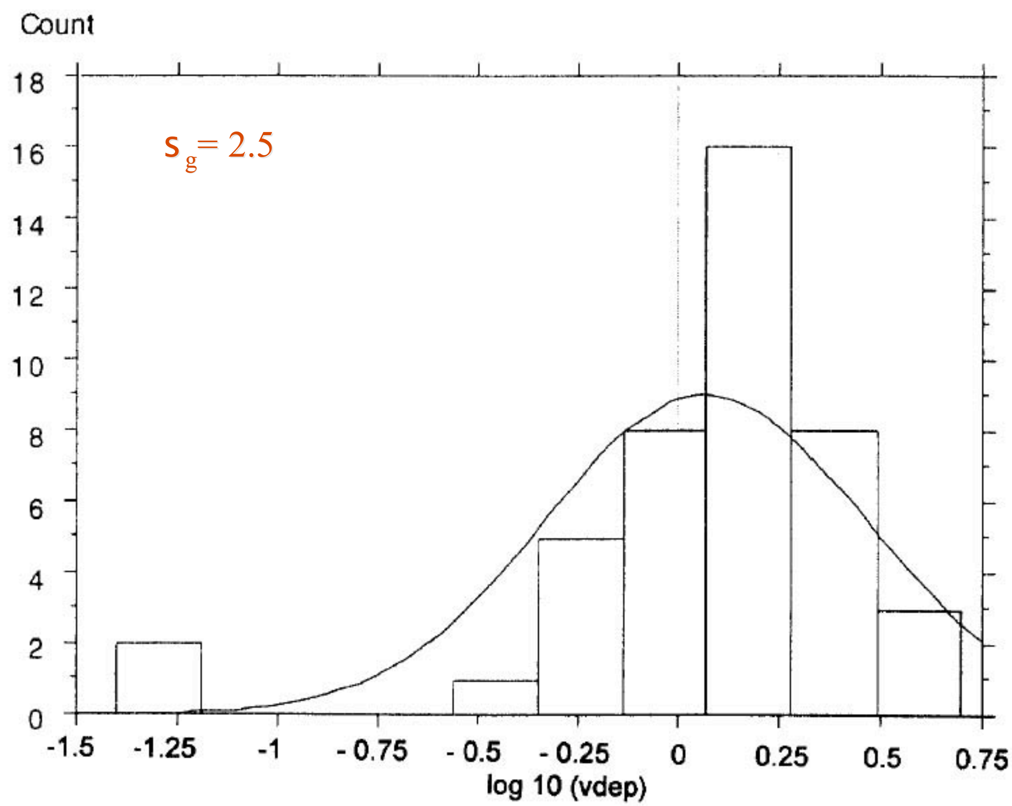
- 1-standard deviation confidence interval
  - The damage cost methodology is a multiplicative approach.
  - According to Central Limit Theorem, a lognormal distribution is the "natural" distribution for product functions.
  - The distribution of errors is approximately lognormal because the dominant terms in the calculation have distributions not far from lognormality.
  - The confidence intervals (CI) about the median *Estimate* and expressed in terms of the geometric standard deviation σ_G.

$$68\%\ CI = \left[\frac{Estimate}{\sigma_G}, \quad Estimate \times \sigma_G \right]$$

  - σ_G = 2-3 (chronic) and 4 (acute) for mortality; 3 for morbidity; 6-8 for cancers, and 3-4 for crops/materials

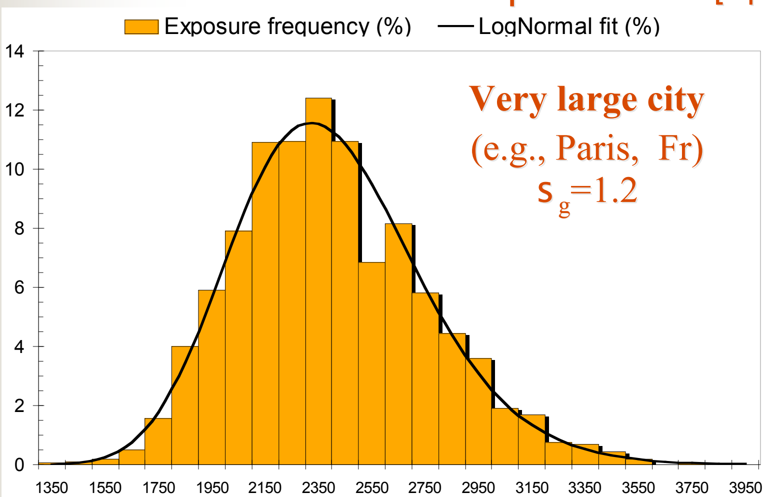
Uncertainty of Results (3)

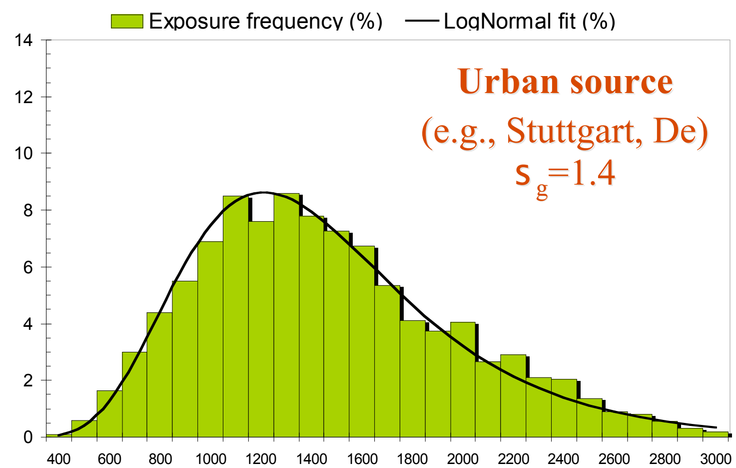
- Examples of data and model uncertainty
  - Distribution and lognormal fit to SO_2 dry deposition velocities (cm/s) over different surfaces [Sehmel, 1980; see Rabl and Spadaro, 1999]

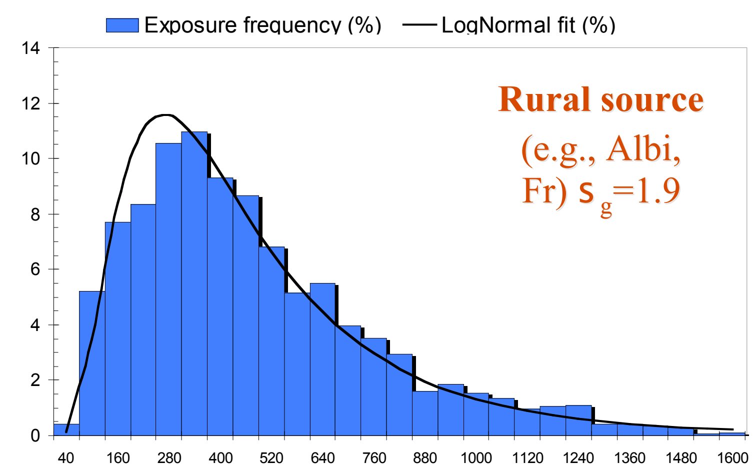


Uncertainty of Results (4)

- Examples of data and model uncertainty
  - Distribution and lognormal fit to collective population exposure (pers.mg/m^3) for several European sites [Spadaro and Rabl, 2005]

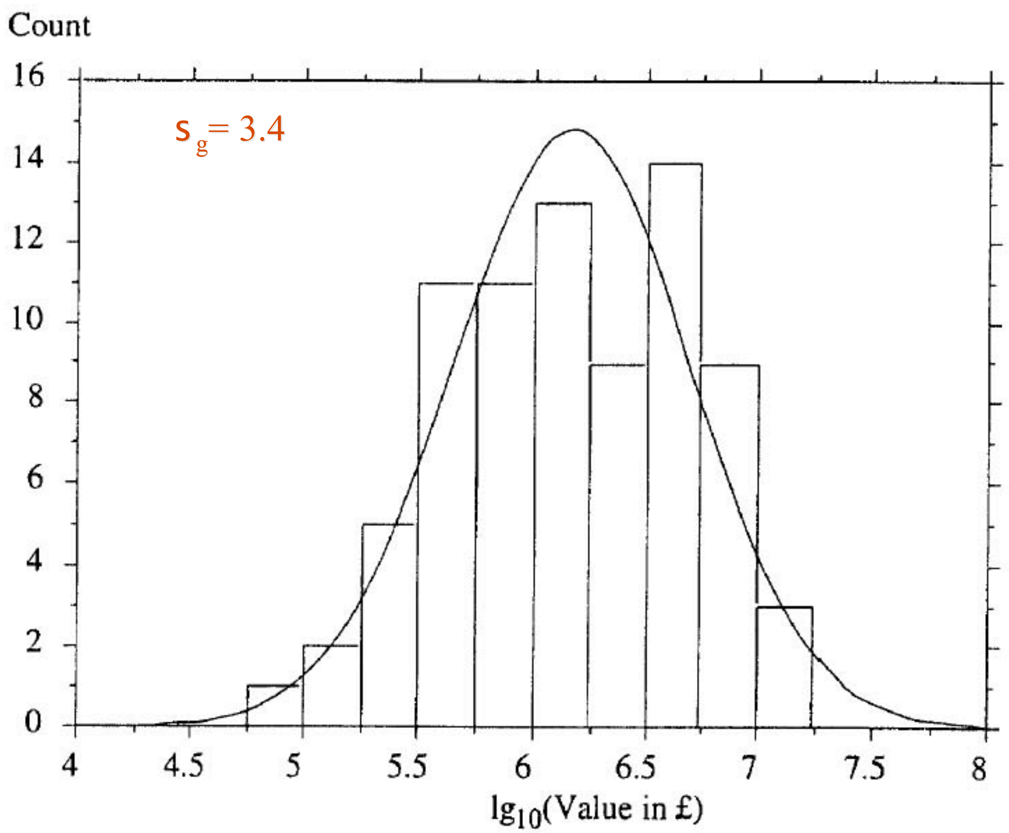






Uncertainty of Results (5)

- Examples of data and model uncertainty
  - Distribution and lognormal fit to statistical value of life estimates
    [Ives et al., 1993; see Rabl and Spadaro, 1999]



Uncertainty of Results (6)

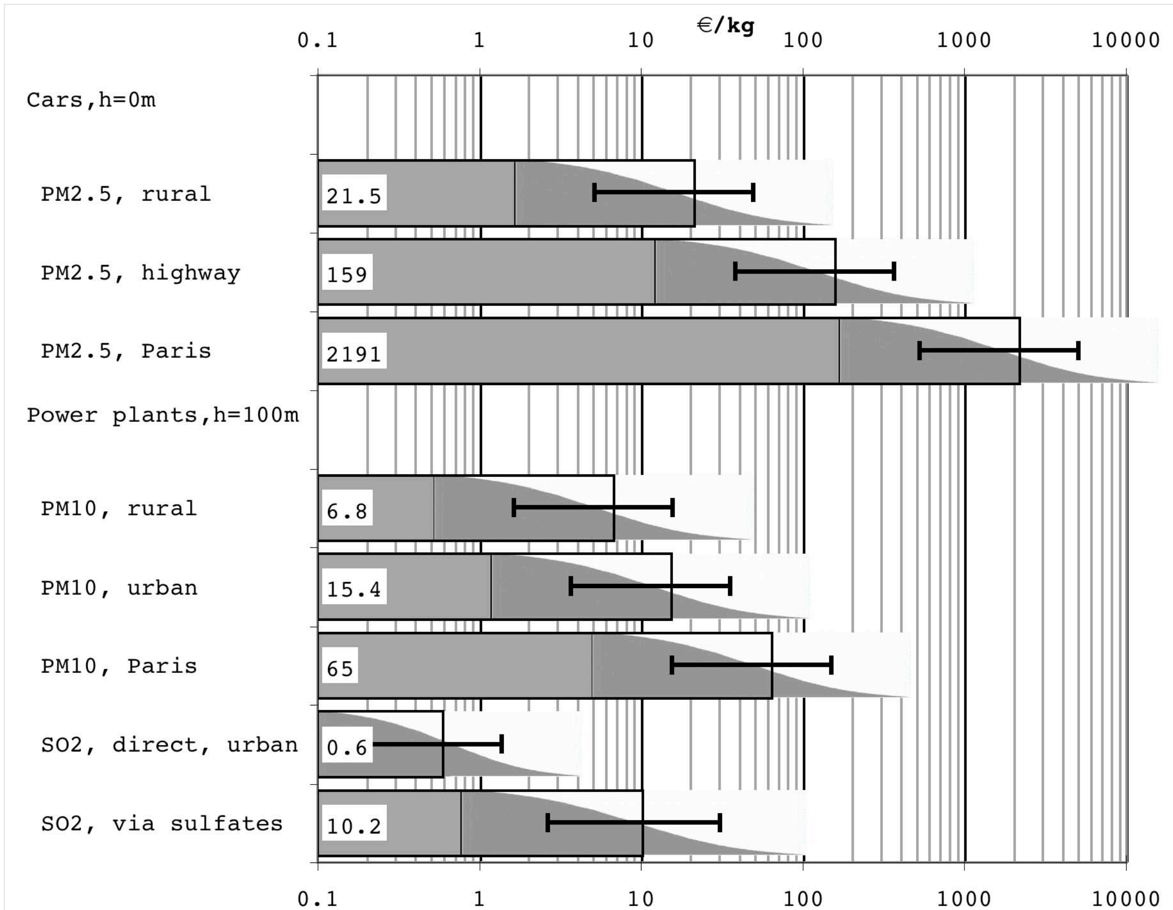
- Sample calculation of impact pathways overall geometric standard deviation, $\ln^2(s_{gtot}) = S \ln^2(s_{gi})$ [Rabl and Spadaro, Feb 05]

	lognormal?	σ_{gi} PM	*$ln(\sigma_{gi})^2$*	σ_{gi} SO_2 via sulfates	*$ln(\sigma_{gi})^2$*	σ_{gi} NO_x via nitrates	*$ln(\sigma_{gi})^2$*
Exposure calculation							
Dispersion	*yes*	1.5	*0.164*	1.5	*0.164*	1.5	*0.164*
Chemical transformation	*yes*	1	*0.000*	1.2	*0.033*	1.4	*0.113*
Background emissions	*no*	1	*0.000*	1.05	*0.002*	1.15	*0.020*
CRF							
Relative risk	*no*	1.3	*0.069*	1.3	*0.069*	1.3	*0.069*
Toxicity of PM components	*?*	1.5	*0.164*	2	*0.480*	2	*0.480*
YOLL, given relative risk	*no?*	1.3	*0.069*	1.3	*0.069*	1.3	*0.069*
Monetary valuation							
Value of YOLL (VOLY)	*yes*	2	*0.480*	2	*0.480*	2	*0.480*
Total		**2.65**	***0.95***	**3.13**	***1.30***	**3.26**	***1.40***

Conclusion: 68% CI is ⅓ to 3 times the median estimate

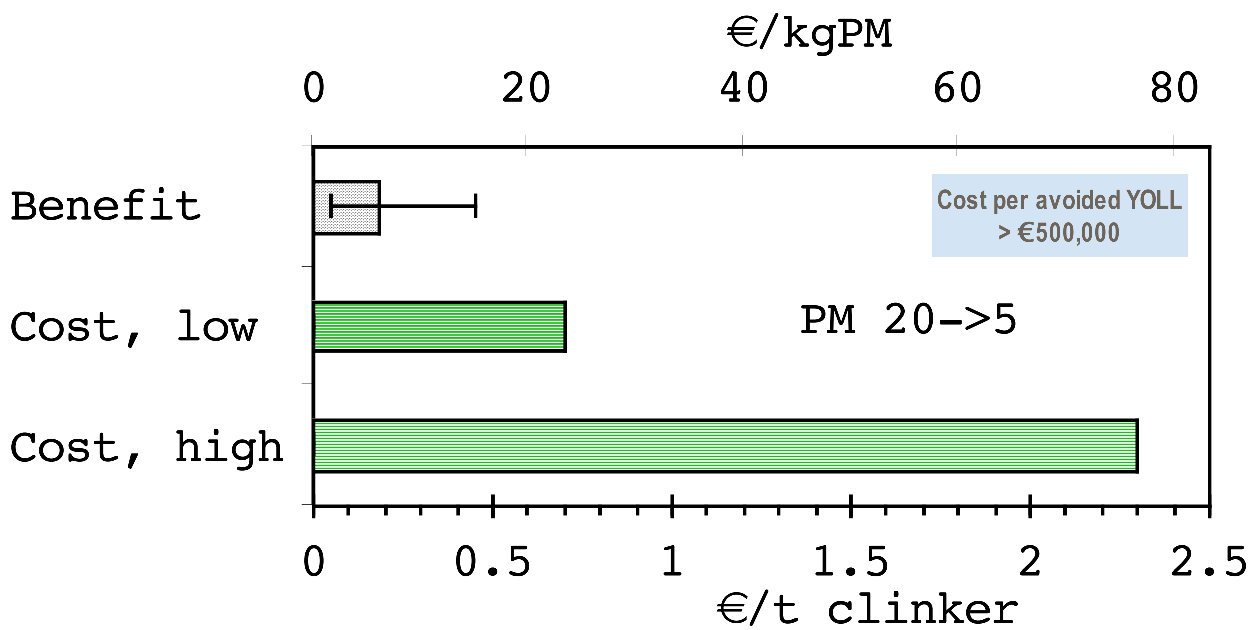
Uncertainty of Results (7)

- Presentation of results and uncertainty [Rabl and Spadaro, Feb 05]



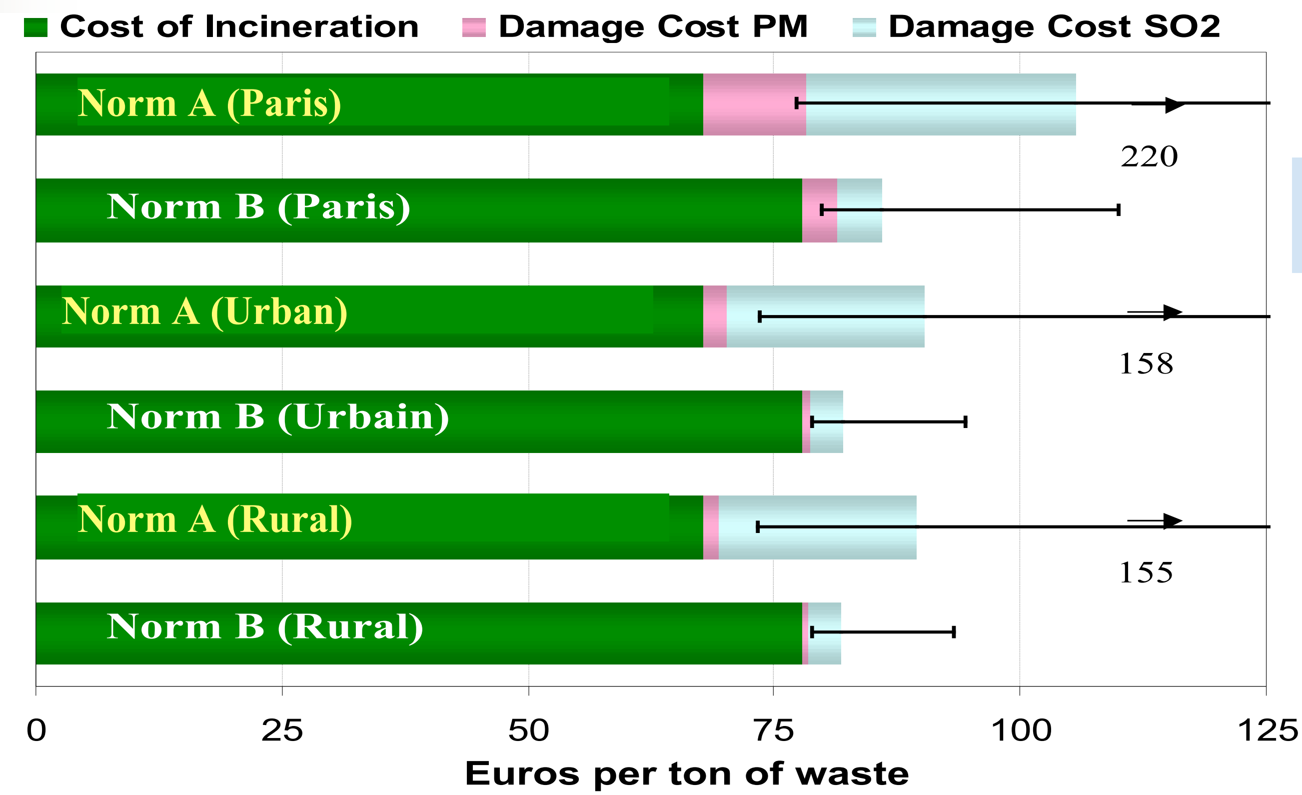
CBA of EU emission limits for cement industry

- Was the reduction of particulate matter (PM) emission limits for cement kilns that co-incinerate waste as fuel from 20 to 5 mg/Nm^3 justified (EU Directive of 2000)?



Answer: No, even in view of the uncertainty.

CBA of emission limits for municipal solid waste incineration



Cost per avoided YOLL

€40,000 to €85,000

Regulation A [PM = 30 mg/Nm^3; SO_2 = 300 mg/Nm^3]

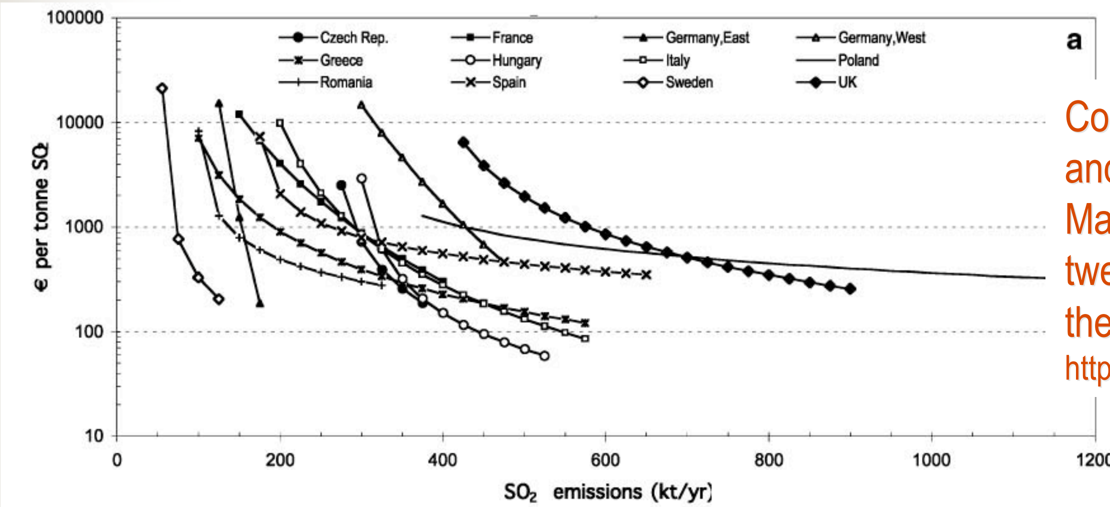
Regulation B [PM = 10 mg/Nm^3; SO_2 = 50 mg/Nm^3]

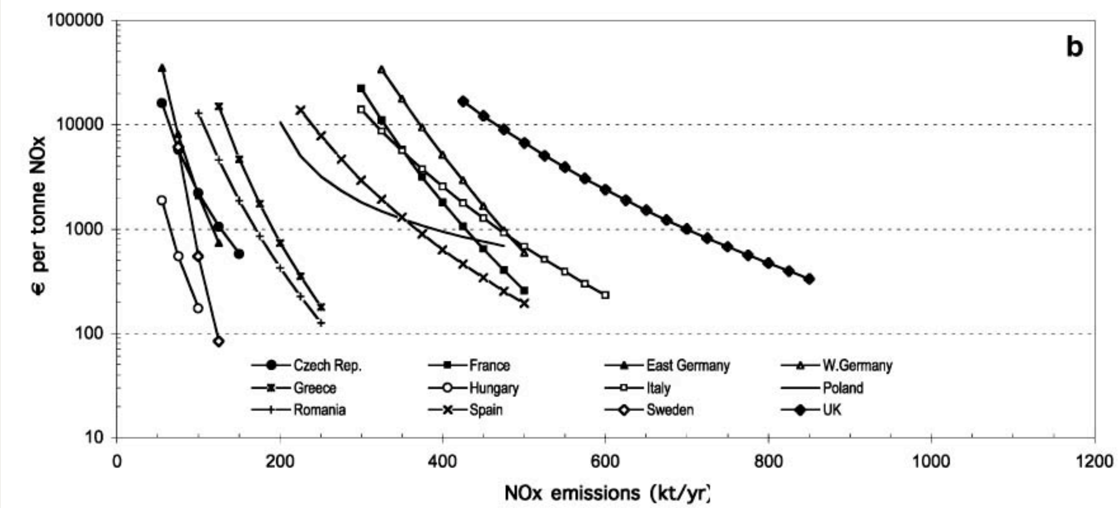
Answer: Yes, likelihood that total cost will increase is small

“How large is the cost penalty if one makes the wrong choice because of errors or uncertainties in the cost or benefit estimates?”

- The usefulness of damage costs is often questioned because the uncertainties are so large, factor of three about the median value (see previous slides).
- It should be emphasized, however, that the uncertainties by themselves are not intrinsically useful, but rather the uncertainty should be viewed within the broader context of the choice of policy options or scenarios available to the decision-taker.
- As it happens, for continuous policy choices, the effect of uncertainty is surprisingly small because near an optimum the total social cost (abatement plus damage cost) varies slowly as individual cost components are varied over their ranges.

"How large is the cost penalty if one makes the wrong choice because of errors or uncertainties in the cost or benefit estimates?" (2)

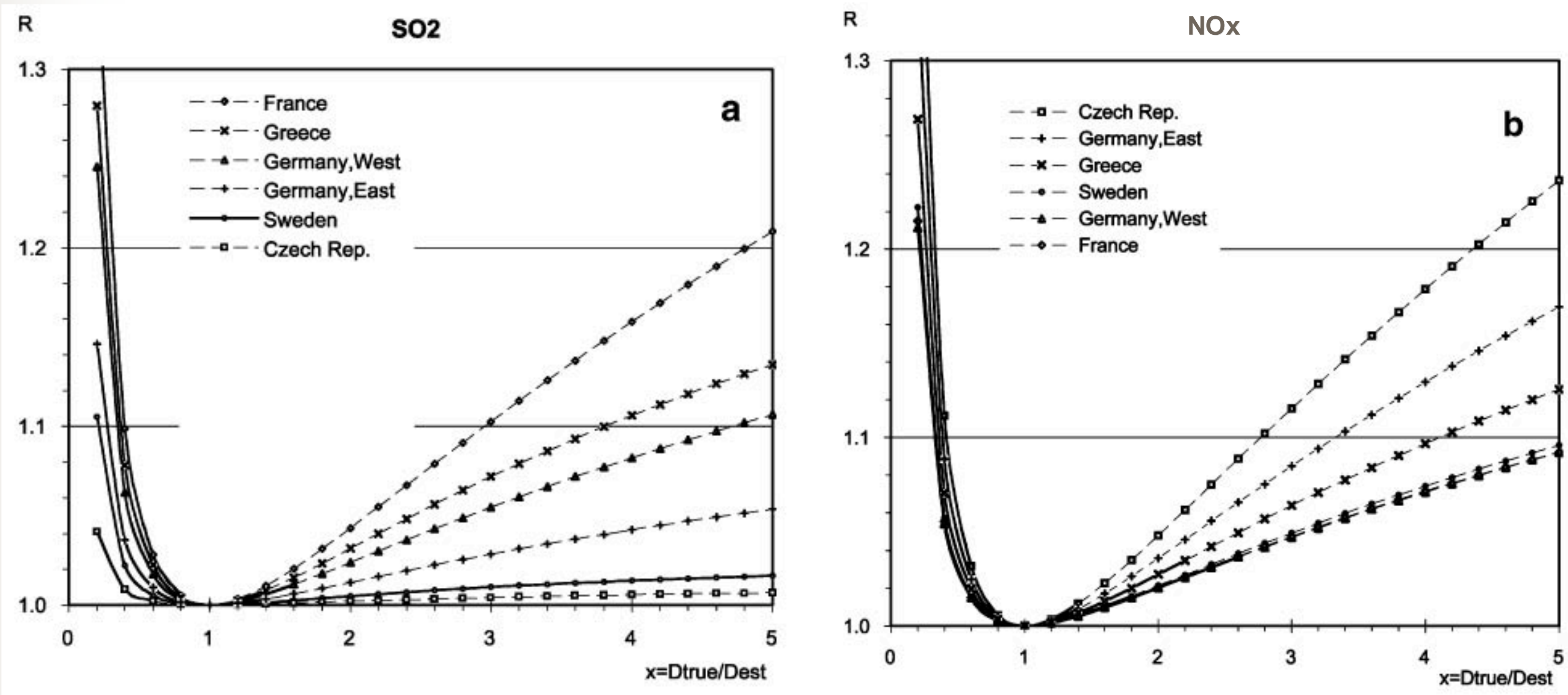




Consider, for example, the case of NOx and SO_2 national emission ceilings. Marginal abatement cost curves for twelve European countries are shown in the figures to the left [IIASA, 1998; http://www.iiasa.ac.at/~rains/reports/updapp6.pdf]

“How large is the cost penalty if one makes the wrong choice because of errors or uncertainties in the cost or benefit estimates?” (3)

- The cost penalty ratio R, defined as the relative increase of the total social cost (abatement cost plus damage cost) above the “true” optimum value, is presented below as a function of x, the error in the damage cost estimate.



- Even an error by a factor of three in the estimated damage cost only results in a cost penalty of 20%.

Source: Rabl, Spadaro, and van der Zwaan (2005)

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RiskPoll: A model for quantifying air emission impacts and damage costs to human health and the environment

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THANK YOU….